# A FRAMEWORK FOR ANALYZING THE SUSTAINABILITY OF PEER PRODUCED SCIENCE COMMONS

BY

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DISSERTATION

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# ABSTRACT

## 0.1 Abstract

The sustainability of eScience research infrastructures is an increasingly complex problem addressed by science and technology policy. Through a case study of the International Comprehensive Ocean and Atmosphere Dataset (ICOADS) I describe a common property regime for sharing and pooling resources across traditional organizational boundaries, and the collective action needed to sustain this arrangement in the face of political, social, and economic change. I use this work to support the testing and refinement of an analytical framework. The contribution of this work will be a better understanding of how institutions for collective action evolve, and a framework for reducing the complexity of studying eScience commons

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# CHAPTER 1

In fields that study complex physical systems, such as climate science, the production of reliable knowledge is often beyond the capabilities of any one person or group. To overcome these individual limitations climate science engages in a form of collective action where many people, institutions, and organizations effectively cooperate to share information and pool resources in pursuit of a common goal (Oliver & Marwell, 1993). Increasingly this work is made possible by access to publicly funded infrastructures, including archives of openly accessible data, suites of open-source software, and high performance computing facilities (Berman & Cerf, 2013). Many of these infrastructures are funded by government subsidies in the form of research grants or cooperative agreements between a federal agency and a research laboratory (Sarewitz, 1996). A substantive question for science and technology policy makers is how to best support these emerging arrangements so that investments in infrastructure and other durable resources are beneficial to the immediate needs of basic science research, but are also sustainably managed and preserved for the benefit of future generations.

Although there is an abundance of literature that addresses collective action in scientific collaborations (e.g. Sonnenwald, 2007) this work tends to focus on variables leading to the success or failure of these arrangements (e.g. Finholt, 2002), and therefore draws conclusions about how to design *new* infrastructures to support eScience research (Jirotka et al., 2013). Few studies have looked at the sustainability of these cooperative arrangements, how they evolve over time, or how the design of policies that underlie the effective functioning of these collaborations in turn impact the ability of diversely motivated groups to solve collective action problems.

## 1.1 Research Questions

This dissertation will develop a case study of the International Comprehensive Ocean and Atmosphere Dataset (ICOADS), a cooperative project that develops, distributes and has sustained an archive of marine climate information (data, software, documentation, etc) over a thirty year period. This case study will provide a valuable understanding of the ways in which scientific institutions for collective action evolve in the face of social, political, and economic change.

The specific research questions that this case study addresses are:

> **RQ1** : How does ICOADS, as an institution for collective action, overcome transaction costs in organizing its production of new knowledge?
>
> **RQ2** : How has ICOADS, as a project with particular governance arrangements, evolved in response to external pressures from funding agencies, the politicization of climate related research, and rapid technological change?

A major argument of this proposal is that science and technology policy struggles to reliably address issues of sustainability, in part, because social scientists studying cyberinfrastructure development, data sharing and reuse, or eScience collaboration more generally, have failed to provide an adequate base of knowledge for decision makers to consult in designing policy interventions (Miller & Neff, 2013). This is not because this work lacks in quality or relevant research findings, but as a result of these studies being so different in the levels and units of analysis, the presentation of findings, and disciplinary cultures that privilege theory construction over policy relevance.Too often valuable knowledge about governance, and the role of federal policy in successfully functioning collaborative arrangement remains isolated and difficult to meaningfully integrate (Jackson et al., 2013, 2014).

If science and technology policy is to move beyond simple panaceas for solving the complex interrelated problems of sustaining sociotechnical systems then it requires integrating knowledge from many different studies of cooperation, coordination and collaboration in eScience. I argue that this can be accomplished in developing analytical frameworks that specify a set of variables to be studied, and the different levels of interactions that are to be analyzed across cases. This requires frameworks that are flexible enough to be used in a variety of settings and by a diverse number of researchers, and yet rigid enough to produce findings that are comparable to one another in meaningful ways. The challenge for this approach is, as Jirotka, Lee and Olson recently put it, "finding ways to make the complexity of socio-technical e-Science configurations more tractable without being reductionist" (2013, p. 31).

Institutional scholars working in diverse fields like land and fisheries management, ecology, and political science have for many years been successful at producing frameworks for the analysis of sustainability in socio-economic settings (Ostrom, 2007b). This is accomplished by leveraging systems and complexity theory (Ostrom, 2007a) to identify concepts like stock flows, feedback loops, and emergent properties that reductionist thinking often simplifies or overlooks (Meadows, 2008). My third research question then asks:

> **RQ3**: How can analytical frameworks successful for studying collective action problems in other domains be modified for sociotechnical settings where issues of sustainability, cooperation and shared resource management are diverse and shifting over time?

In the rest of this chapter, I argue that these are particularly relevant questions to ask about institutions that are facing budget crises as a result of the politicization of climate research, and that the International Comprehensive Ocean and Atmosphere Data Set (ICOADS) project is an appropriate subject for this work.

## 1.2 ICOADS

The International Comprehensive Ocean and Atmosphere Dataset (ICOADS) is a cooperative project that curates, develops and distributes quality controlled data, metadata, historical documentation, and software to the climatology community. The project, originally named COADS, was initiated in 1981 by researchers at the Earth System Research Laboratory (ESRL), the National Climatic Data Center (NCDC), and the National Center for Atmospheric Research (NCAR). Over time the project grew to include international collaborators, and the name was changed to International COADS in order to reflect the contributions of organizations like the Joint World Meteorological Organisation (WMO), the Intergovernmental Oceanographic Commission (IOC), and the Technical Commission for Oceanography and Marine Meteorology (JCOMM).

Contemporary data curated by ICOADS come from a variety of sources, including the Global Telecommunications System (GTS), in-situ measurements taken by sea-faring vessels, earth observing satellites, and both drifting and moored buoys. Historical data come from the original 1981 effort to aggregate existing marine data records from maritime archives around the world, as well as a continual stream of historical records that have been rediscovered, or newly digitized. Data sources also now include the use of crowdsourcing efforts to transcribe weather recordings taken by military, shipping, and whaling voyages from the 17th, 18th, and 19th century[1] (Brohan et al., 2009).

The labor-intensive process of taking heterogeneous records from different observing platforms, and uniformly processing and integrating the data into a larger set of historical observations is the major value of ICOADS ongoing work. This includes the preservation of provenance metadata that is recorded for each individual record, allowing for researchers to trace backwards in time to verify whether the source of a supposed climate anomaly is genuine or the result of a data processing error.

[1] To give some indication of how much the project has grown over time, the first release of COADS data products contained 73 million records with dates reaching back to 1852. As more shipping records have been discovered and digitized the coverage of ICOADS has been extended to 1662, and now includes more than 261 million records. (Woodruff et al., 2011)

## ICOADS Funding

The production of ICOADS was originally meant to fill a gap in climate change research which lacked an authoritative source of data for the boundary conditions occurring at the ocean and atmosphere interface. Although this was widely acknowledged as an important next step in earth systems research, ICOADS partners struggled to attract funding for their work. As a preface to the first release of COADS one of the principle investigators noted that, "It has taken four years and much effort by many individuals and several institutions to obtain and process the hundreds of tapes containing the basic data input. All of this effort was provided from ongoing activities; there was no appropriation identified for the task. It is a tribute to the spirit of cooperation among the participating organizations that the task has been successfully completed" (Slutz et al., 1985). Even though the project was unfunded the developers of ICOADS release 1.0 committed to making all of its products (data, software, etc.) freely available to the climate science community (Worley et al., 2005).

Free and open access to ICOADS has helped it become recognized by the climate community as "the most complete and heterogeneous collection of surface marine data in existence" (Woodruff et al., 2011). ICOADS data have been used extensively in earth systems science research, international climate assessments such as the IPCC AR4 and AR5 reports, as well as reanalysis projects that combine historical weather observations with climate data to create authoritative datasets for the climate modeling community (Kalnay et al., 1996). However, the success and widespread use of ICOADS has not resulted in greater stability for the funding of the project. This is due in part to the difficulty in calculating the research impact of many different ICAODS products (Weber et al., 2014), as well as an overall decrease in federal funding for the maintenance of research infrastructures (Berman & Cerf, 2013). The politicization of climate related research has also impacted ICOADS funding in recent years. In the winter of 2012, this became a major issue for the sustainability of the project, as NOAA announced that:

> For budgetary reasons, stemming from pending large cuts at the NOAA Climate Program Office (CPO), ESRL Directors have determined that it is no longer feasible for its Physical Science Di-

> vision (PSD) to continue supporting any further ICOADS work–effective immediately (Lawrimore, 2012).

By operating as a cooperative, funding would still be available for the maintenance and curation of ICOADS data through NCAR (NSF), but the project could not plan major updates to the software or documentation that complements ICOADS data, and a much anticipated third release was delayed indefinitely.

### Studying the ICOADS Community

My work with the ICOADS community began as an Advanced Studies Program (ASP) fellow at NCAR in the summer of 2012. I was originally interested in asking research questions about the evaluation of federally funded research and development centers (FFRDCs), and the co-production of knowledge between climate scientists and policy makers. My initial work on these questions took a grounded theory approach (Corbin & Strauss, 2008), using NOAA's defunding of ESRL as a critical incident to ask questions about how ICOADS was evaluated by policy makers, and its general impact or importance to knowledge production in climate science (Flanagan, 1954).

Below, I present findings from this work. I describe how these studies helped me to generate a new set of research questions about public goods, collective action, and the sustainability of cooperative work more generally. Each of the studies described below were collaborations with software engineers and project scientists at NCAR, as well as colleagues at the Center for Informatics Research in Science and Scholarship (CIRSS). However, I conceived of and designed each study, conducted the majority of all data analysis, and I am the first author on all but one of the resulting publications from this work (of which I am the co-first author).

## 1.3 The Data Usage Index

Federally funded research and development centers typically measure the levels of service they provide to end users through descriptive statistics, such as the number of times a data file has been downloaded over a given period of time. To better understand the use of ICOADS in the climate science community my first research project used log analysis techniques from Information Science (Jansen, 2006; Nicholas et al., 2005), and in particular a Data Usage Index (hereafter referred to as DUI) used in the life sciences. The DUI was originally designed to measure the impact of institutional contributions to the Global Biodiversity Information Federation Database (GBIF) by using *indicators* of how data were discovered and accessed (i.e. number of downloads, page hits, files contributed by an institution, etc.) (Chavan & Ingwersen, 2009). In the DUI, indicators are extracted from user query logs and combined in simple, but unique ways to calculate impact factors (Ingwersen & Chavan, 2011, ; See Appendix A, Table 1).

Initially, our work aimed to modify the DUI's indicators from the context of a biodiversity database to the Research Data Archive (RDA) at NCAR, which hosts and serves climate data and software (including ICOADS). To do this we developed a set of use cases based on a researcher's discovery, selection, and mode of access to different data products from the RDA.

From the use cases we identified six key indicators that were captured in the RDA's logs, as well as potentially informative relationships between these indicators (see Table 1 below).

| **Code** | **Indicator** | **Explanation** |
|---|---|---|
| uu(ds) | Unique Users | Unique users that downloaded data during a time window |
| n(ds) | Number of Datasets | Number of Datasets assigned DS number by RDA |
| f(ds) | Files DS | Number of files in Dataset per time window |
| d(ds) | Download Frequency | Total number of files downloaded per time window |
| hp(ds) | Homepage Hits | Home Page Hits of Data Set per time window |
| d(ds) /uu (ds) | Download Density | Average number of files downloaded per unique user |
| d(ds) / f (ds) | Usage Impact | Total number of downloaded files over total files in dataset |
| d(ds) / hp(ds) | Usage Balance | Files downloaded by number of homepage hits per time window |
| hp(ds) / f(ds) | Interest impact | Total homepage hits per number of files in dataset |
| hp(ds) / uu(ds) | Secondary Interest Impact | Total Homepage hits over unique users |
| ss(ds) / d(ds) | Subset Ratio | Subset requests over total number files downloaded |

The completed use cases also demonstrated that two user types could be identified based on how data were accessed:

- **Programmatic Users**: accessed or downloaded data through a command line tool (e.g. '-curl [ˆcurl] or 'wget' [ˆwget]) or through a scripting language.

- **Assisted Users:** access data via the graphical user interface, or by subset requests made through a separate tool developed by the RDA staff.

**Methods**

To test the effectiveness of the modified DUI three different RDA data products were selected - including the most recent release of ICOADS (version 2.5). Indicators from the completed use-cases were then extracted from the user logs of each dataset over a sixteen month period. This resulted in an index for each of the three datasets (See Appendix A).

From the index of each dataset we then further calculated two impact factors:

**Usage Impact Factor**

$$(d(u)/f(u))/\sum_{1}^{n} d/\sum_{1}^{n} f \tag{1.1}$$

where (u) is the given resource unit, (d) is the download frequency of users, (f) is the number of files downloaded per user session, and (n) is the total number of units (files available in the dataset) in the denominator.

**Interest Impact Factor**

$$(hp(u)/f(u))/\sum_{1}^{n} hp/\sum_{1}^{n} f \tag{1.2}$$

which is identical to UIF except download frequency (d) of users is replaced by the number of homepage hits (hp) a dataset receives.

**Outcomes**

The Usage and Interest Impact Factor scores that we calculated were not significant for any of our use caes. This ultimately led us to conclude that these metrics were not valid for policy related impact assessments. However, the indexes did prove to be a useful tool in tracking curatorial interventions (Weber, Thomer, Mayernik, et al., 2013). RDA curators were able to use the indexes to better understand usage patterns within different data communities, and to explore changes in the way that a dataset was accessed over time. As an example of the latter point, the ICOADS Usage Impact Factor scores declined over the sixteen month period of our study; dropping significantly before the summer of 2011 and continuing at a low rate through 2012. A long-time curator of ICOADS explained that this could be the result of having added new software to the repository that spring. This software was developed to help users subset new ICOADS data that were formatted differently from previous releases. The software was meant to decrease the total number of files a user needed to download, and speed up applications built to regularly harvest data from the RDA.

We investigated this hypothesis by dividing the indicator scores based on the two user types (programmatic and assisted). After doing this, we observed a significant upward shift in the total number of programmatic users of ICOADS, and an overall decrease in the number of files that were downloaded over the same time period. We also found a number of modifications of the software posted to on-line discussion forums for ICOADS[2].

That the software increased the efficiency of the archive, but simultaneously decreased the impact factor scores seemed logical - this was a result of the designer of the study (me) not understanding the function of the archive well enough to develop a robust set of impact metrics. But, finding modifications of the software posted to public repositories was puzzling. If the research environment is so competitive that ICOADS was being defunded then why would researchers, all of whom are interested in the same resource, help each other to work more efficiently?

To put this into economic terms, obtaining information assets in the ICOADS

[2]To be cautious, what we observed in this instance is a loose correlation between user types and the total amount of files downloaded. We don't know with any amount of statistical certainty that the introduction of new software caused users to become more efficient in their downloading, and without further examples of this phenomena we can't say whether or not the finding would be replicated in other communities

community requires users to exchange and share a number of *transaction costs*. In organizing economic productivity, individual actors are typically able to overcome high transaction costs in one of two ways: through a marketplace where prices are “naturally borne out” of exchange and so individuals follow pricing signals, or by coordinating their actions through a firm where individuals follow a hierarchy of decision making (Coase, 1937; Williamson, 1975).

In looking at the small example of software modification it appears that neither model explains how the ICOADS community organizes itself to overcome transaction costs. These unselfish acts also directly contradict the private property, self-interested model being used to describe resource sharing in other eScience settings (e.g. Birnholtz & Bietz, 2003; Zimmerman, 2008; Wallis et al., 2013). For ICOADS, overcoming transaction costs in producing new knowledge seemed more similar to open-source software projects, and what Benkler called *commons-based peer production*, where economic productivity is “radically decentralized, collaborative, and nonproprietary; based on sharing resources and outputs among widely distributed, loosely connected individuals who cooperate with each other without relying on either market signals or managerial commands” (2006, p. 60).

In working with colleagues at NCAR my observations about the unique way in which ICOADS is produced led to the first research question to be answered in this dissertation:

**RQ1** : How does ICOADS, as an institution for collective action, overcome transaction costs in organizing its production of new knowledge? If peer production is indeed the model by which this is achieved:

RQ 1.1 How, and/or in what ways does it differ form other forms of peer production?

RQ 1.2 How does ICOADS sustain these successful cooperative arrangements?

RQ 1.3 What are the activities of its community members necessary to achieve this sustained success, and how can those actions be recognized, either formally or informally, over the duration of the project's existence?

## 1.4 The Genealogy of ICOADS

ICOADS is widely reused in developing new climatology data products, but tracking the reuse of ICOADS through citation analysis is limited by the inconsistency in how the project is acknowledged, and what is subsequently cited (e.g.The dataset hosted at the RDA?, A paper describing the dataset?, By thanking individual curators in an acknowledgment section?) (Weber, Mayernik, and Worley, 2014).

To better understand the history of how ICOADS has been reused, we conducted a second study using techniques from the field of evolutionary biology (Page & Holmes, 2009) and cultural analytics (Mace & Holden, 2005) to produce a genealogy of ICOADS. Our inspiration for this work came from a set of studies that looked at the history of climate models by tracing their relatedness (See Figure 1.1); The figure on the left is from a study conducted by Edwards, who created a "family tree" of Atmospheric General Circulation Models (AGCM) from archival documents and oral histories (2010). The figure on right is a dendrogram showing relatedness of climate models that participated in the 5th Climate Model Intercomparrison Project (CMIP), constructed using principal component analysis on documentation available for each model (Knutti et al., 2013).

Our work on an ICOADS genealogy somewhat diverges from these previous studies in that we aren't making an evolutionary metaphor or analogy, we are directly borrowing techniques and software from phylogenetics (Page & Holmes, 2009) in trying to quantify and subsequently visualize the relatedness of climate data. Part of the ambition in taking a biological approach to studying material aspects of ICOADS was to leverage the explanations and theories that this field offers for cooperation (Nowak, 2006). If ICOADS data products did have a traceable evolution then it might be possible to use concepts like kin selection, fitness, group selection, and reciprocity (direct, indirect and network) to shed light on how the data have been reused, shared, developed, or refined. We were not trying to create a direct map-

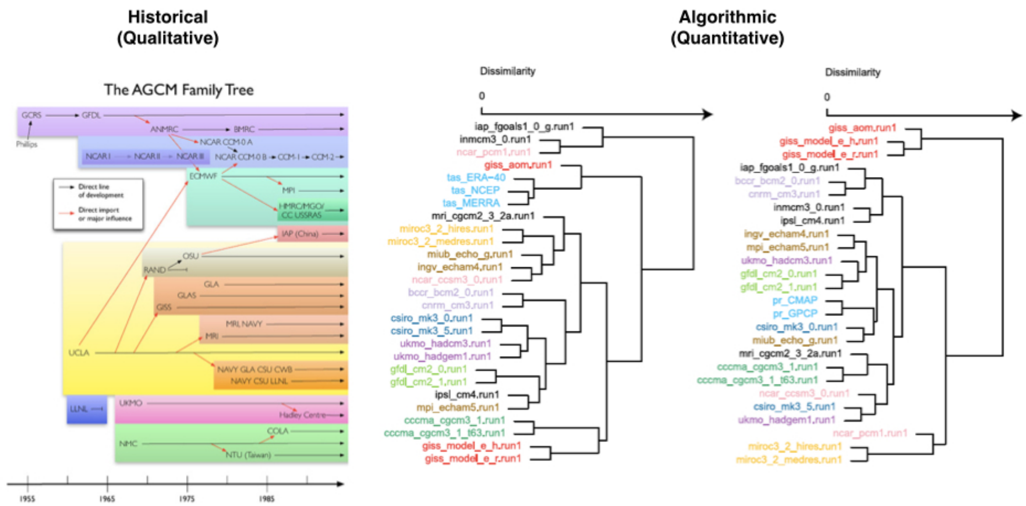


Figure 1.1: Two previous genealogical studies in climate science. (Left: (Edwards, 2010); Right: (Knutti et al., 2013))

ping between biotic reproduction and abiotic data reuse, but we were taking seriously the ecological metaphor that is often invoked in discussing the complexity of software / data intensive enterprises (Weber, Thomer, & Twidale, 2013).

### Methods

To trace the genealogy of ICOADS, we searched for and harvested metadata records from NASA's Global Change Master Directory (GCMD) using the ISO 19115 standard. We used queries related to ICOADS such as "International Comprehensive Ocean and Atmosphere Dataset" or "I.C.O.A.D.S" to locate as many ICOADS records as possible. In total, we discovered 99 records, of which only 23 represented different versions or subsets of the ICOADS project. This means that the remaining (n =76 ) records represented derivatives or offspring of ICOADS.

We then identified properties (or characteristics) of climate datasets which we thought would be unique and important to signifying change from one generation of ICOADS data to the next. This included things like format, encoding, or the available parameters of the data set. We then extracted fields containing these properties from the metadata records. The fields harvested included: Entry Title, Entry ID, Summary, Geographic Coverage,

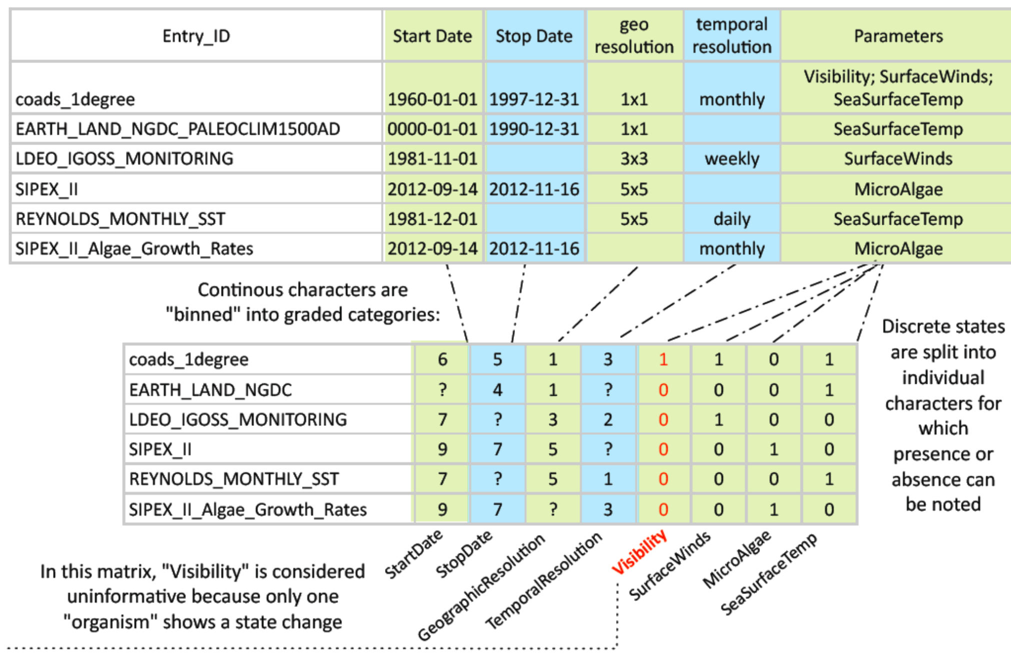


Figure 1.2: The migration of metadata records (top) to a character matrix (bottom). Uninformative characters like the one shown (Visibility) cannot show extensive relatedness between groups of ”organisms” (Adapted from Thomer and Weber, 2014)

Start Date, End Date, Geographic Resolution, Temporal Resolution, Scientific Keywords (often dataset parameters), Geographic Keywords, Sources (platform of data collection), and Instruments.

Next, we converted each field into binary codes for “presence” or absence” of individual keywords (Figure 1.2). In some cases we coded additional “presence” or “absence” of characters based on the free text summaries of the records (for instance, in some cases, resolution was stated in the free text “Summary” field but not the “Geographic Resolution” field).

With the coded data, we then produced a maximum likelihood (ML) tree (Felsenstein, 1981), by utilizing a statistical model specifically designed for use with morphological, or presence/absence data (Lewis, 2001). Again, the assumption that we were making in this process is that significant properties or characteristics of the metadata records could be clustered - such that data products that shared similar traits could be grouped together in the same way that similar species are grouped together in a phylogenetic analysis (for a complete discussion of this work see Thomer & Weber (2014); Weber, Thomer, and Worley, 2014).

Our preliminary efforts were successful in creating a tree that chronologically resembled the release schedule of ICOADS (e.g. the root node was the earliest release of ICOADS and furthest nodes were latest releases). To evaluate the accuracy of this work, we presented a poster at the Fourth JCOMM Workshop on Advances in Marine Climatology, which is a major event in the ICOADS community. We asked participants to annotate our tree, and give us feedback on:

1. The accuracy of the clustering of related datasets, and
2. Datasets related to or derived by ICOADS that were missing from our tree.

**Outcomes**

The feedback from the ICOADS community verified the accuracy of our work. In particular, many scientists recognized the data products that were clustered based on related features, such as derivative sea-surface temperature (SST) or arctic sea ice data products. However, a number of curators from other data repositories were able to identify missing datasets, and logical relationships between clusters that were not well represented by the tree structure (See Figure 1.3 for annotations).

Many participants also noted that while the phylogenetic tree showed a valid evolution of the data products, the title genealogy was misleading for ICOADS as a project. Notably, the ICOADS community has evolved over time to include international partners that brought different needs, data, software, and skills to the collaboration. For instance, our tree showed that certain data products from the UK's Met Office Hadley derived from ICOADS only very recently, but we couldn't explain that this happened because of a governance change at Hadley that allowed for the data to be obtained by NOAA during this time period (Parker et al., 2004).

In short we succeeded in quantitatively representing the evolution of ICOADS data products, but our work revealed a number of interesting questions to

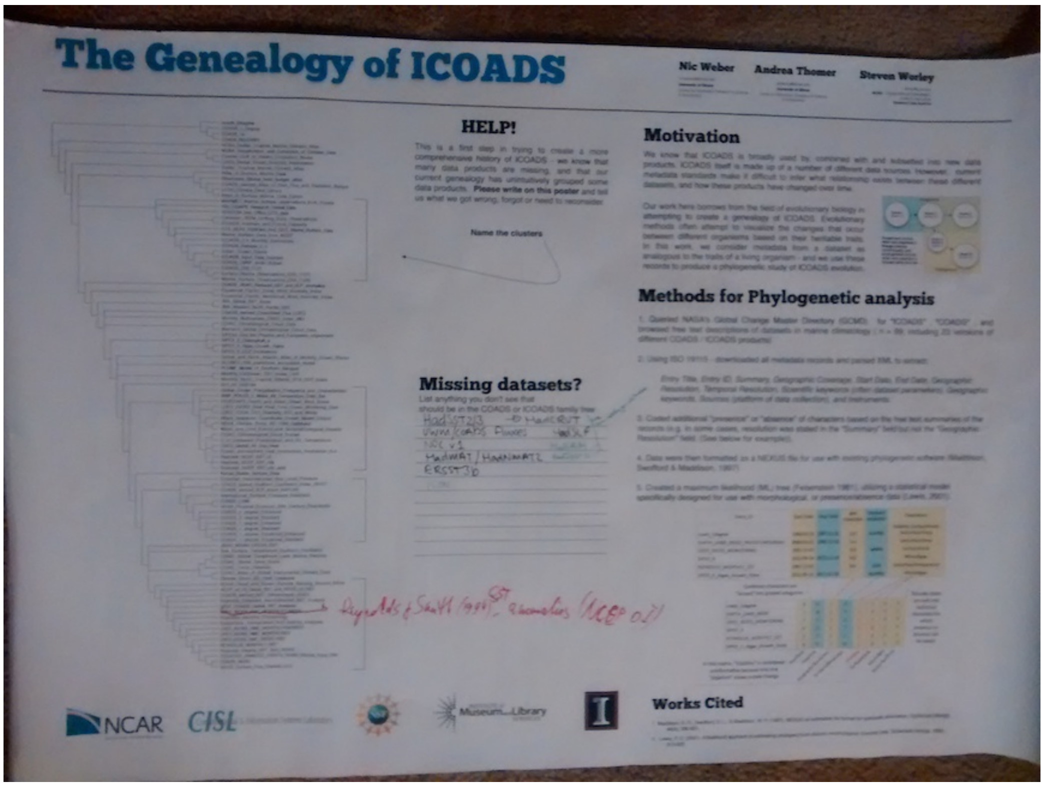


Figure 1.3: Annotations from the ICOADS community on initial draft of ICOADS genealogy

be asked about how external pressures, technological change, and political events shaped the evolution of ICOADS as a project, beyond its material resources. These insights led to a second set of research questions:

**RQ2**: How has ICOADS, as a project with particular governance arrangements, evolved in response to external pressures from funding agencies, the politicization of climate related research, and rapid technological change?

## 1.5 Policy Relevant eScience Studies

In the next chapter I define concepts and identify findings from existing literature that are relevant to my first two research questions. However, a major gap that I recognized in this literature is policy relevant eScience research. By this I mean social scientist who have studied the use, development, or deployment of a technology and the consequences or affordances of that work based on its relationship to federal policies - either surrounding the practice, funding, or management of science and technology applications. This seems a strange gap because many social science studies in eScience settings begin a research paper (journal article, conference proceeding, etc.) by arguing for the relevance of their topic via federal policy documents, such as the the 'Blue-Ribbon Advisory Panel on Cyberinfrastructure' report (Atkins et al., 2002). Too often these studies fail to connect the conclusions and findings of their work back to this arena (Jackson et al., 2013). As a result much of science and technology policy at a federal level struggles to appreciate the complexity of developing and sustaining eScience applications (Katz & Proctor, 2013). If part of the argument being made in eScience studies is that high levels of federal funding investment are an indicator of their importance then it should follow that the work in studying these settings is also of significance to funding agencies. To put it another way, if science policy makes a topic relevant to study then the results of studying that topic should also be relevant to science policy.

So, why have socio-economic and socio-ecologial studies of sustainability been successful at studying institutions while sociotechnical studies have thus far failed to have a strong impact on science policy? Largely because the other domains have developed diagnostic tools and analytical frameworks that allow disparate, unique case studies to be compared to one another so that meaningful design principles can emerge (Ostrom, 2007a).

This leads to my third research question:

> **RQ3**: How can analytical frameworks successful for studying collective action problems in other domains be modified for sociotechnical settings where issues of sustainability, cooperation and shared resource management are diverse and shifting over time?

The major contribution of this dissertation is a framework that will facilitate the integration and combination of different methods to investigate complex, systems-based problems as they relate to the sustainability of cooperative eScience projects. This will be done by incorporating relevant categories from existing sustainability frameworks, and systems theory. In the next chapter, I argue why this is needed from a conceptual standpoint, and how the work of institutional scholars can help address current shortcomings in bringing existing eScience studies to bear on science and technology issues.

# CHAPTER 2

*In chapter two I review literature relevant to a study of cooperation and collective action in an eScience setting. In each section I define a concept, review previous work or background of the concept, and then explain the relevance to ICOADS.*

## 2.1 Peer production

Organizing work on the internet found early success in free libre open source software (FLOSS) projects like Linux, FetchMail, PERL, and Apache. Organizational scholars (Lakhani & Von Hippel, 2003; Lakhani & Wolf, 2005) and economists (Lerner & Tirole, 2002; Hars & Ou, 2001) both marveled at the success of FLOSS projects and their ability solve traditional resource allocation problems outside of either a firm (hierarchy) or a marketplace setting. In this sense, FLOSS projects contradicted many basic economic assumptions about organizing, divisions of labor, and intellectual property (e.g. Coase, 1937; Schumpeter, 1942; G. S. Becker, 1976). A finding often repeated from these early studies of FLOSS development was not that participants were a new breed of altruistic worker, but that organizing projects via networked technologies allows for a more diverse set of interests, preferences, and motivations to emerge than was accommodated by traditional synchronous, face to face venues (Benkler & Nissenbaum, 2006).

In his broad study of open-source software development and the unique legal and economic arrangements that were created by individuals coordinating projects via the Internet, Yochai Benkler described this new mode of organizing as peer production:

> . . . a form of open creation and sharing performed by groups on-

> line that: set and execute goals in a decentralized manner; harness a diverse range of participant motivations, particularly non-monetary motivations; and separate governance and management relations from exclusive forms of property and relational contracts (i.e., projects are governed as open commons or common property regimes and organizational governance utilizes combinations of participatory, meritocratic and charismatic, rather than proprietary or contractual, models)" (2013).

This original definition led to further qualifications of how peer production is accomplished, such as a commons-based model that is, "radically decentralized, collaborative, and non-proprietary; based on sharing resources and outputs among widely distributed, loosely connected individuals who cooperate with each other without relying on either market signals or managerial commands" (Benkler, 2006, p. 61).

Haythornthwaite later drew a distinction between heavyweight and lightweight models of peer production:

- In a lightweight model of peer production, such as crowdsourcing, many loosely connected individuals contribute their effort to accomplishing small, well-defined and highly coordinated tasks.
- In a heavyweight model strongly connected and highly committed members, such as those in a virtual organization (VO), perform loosely coordinated tasks, and their contributions are accepted based on quality control mechanisms like peer review (2009).

## Second Order Peer Production

For social scientists, part of the attraction to studying peer production systems is the *apparent* egalitarian nature of "communal information goods" (Fulk et al., 1996, as quoted inShaw & Hill (2014)). Many of the FLOSS successes listed above have created democratic organizations that have had transformative and lasting success in industries that are traditionally dominated by private firms (i.e. Firefox web browsers, Linux and Android operating systems, etc.). But, after the initial novelty of peer production was described (Benkler, 2006), a series of what might be called second order peer production studies looked closer at these institutions and the context of their success. These studies used quantitative methods to show, for instance, that most FLOSS projects are the work of a few key individuals making large contributions (Shah, 2006); by most measures these individuals are highly uncooperative (Hill et al., 2009); that Wikipedia is a single success in what were many similar wiki-based encyclopedia projects that failed (Kittur & Kraut, 2008; Ortega, 2009); and that the assumed democracy of wiki-based projects actually resembles an oligarchy when studied over time (Shaw & Hill, 2014).

Most recently, organizational scholars have started to turn their attention from what has made the Apaches and Wikipedias of peer production successful towards what has caused similarly structured projects to fail (Shaw & Hill, 2014). This is a familiar turn that can be observed in early CSCW groupware research that first focused on successes (Winograd, 1986) and later on what caused their failures (Grudin, 1988). This pattern is also recognizable in fields like innovation studies where Michael Porter first explained a firm's success through "competitive advantage" (1987), while his protege Clayton M. Christensen later explained a firm's failure through a theory of disruption (2006).

## Peer Production in ICOADS

Many of the features from Benkler's original definition of peer production, such as 'setting and executing goals in a decentralized way' and 'the separation of governance models from management relations,' were simultaneously described in interdisciplinary research settings (Palmer, 2001). In fact, earlier work on scientific collaboration showed that the same set of features could be observed before the widespread adoption of networked technologies like the Internet (Galison, 1997). But, evidence of a shift in how work is accomplished in interdisciplinary settings can be seen, for instance, in the approach to developing earth systems models which evolved from the centrally organized effort of a single institution, to open-source "community models" that couple many different physical system models developed by loosely connected, highly cooperative research institutions around the world - very much following a commons-based peer production as described above (Edwards, 2010; Voinov et al., 2010).

For ICOADS, much of the work that led to the initial development of a “comprehensive” dataset was through the open sharing of data between groups at different institutions, who set and executed goals in a decentralized way, and they did so with little to no external organizing pressure (Slutz et al., 1985). As the ICOADS project grew, it became more diverse and more international. This allowed for developers who were motivated by the need to fill a gap in the data used to calculate climate change indexes to contribute in a loosely coordinated fashion that strongly resembles heavyweight peer production models.

## 2.2 Open science

In short, open science is a set of governance structures that provides a “specific non-market reward system to solve a number of resource allocation problems” (David, 2003). This alternative to privatization applies to both the distribution and production of scientific information as an economic and public good. Open science is the theoretical foundation that allows commons-based property regimes in science to supplant the often private or government controlled rights to access that dominate other spheres of economic activity (David, 2004).

### Open Science and Research Impact

A formidable challenge to adopting open science practices is that a non-market based reward system has yet to fully emerge. This is especially limiting in the academic environment where the promotion and tenure of scientists (and technologists) is still largely based on individual, supposedly merit-based evaluations. So, although there are many emergent practices of openly sharing and pooling resources in domains that rely on open science (Willinsky, 2005; Stodden, 2010), use of traditional market-like mechanisms for measuring performance or impact (e.g. bibliometrics, grant funding levels, etc.) limits their broader adoption. Many alternative scientometric techniques are promoted as a remedy to the limitations of traditional measures of impact (Bollen et al., 2005; Priem et al., 2012; Piwowar, 2013), but as I demonstrated in chapter one, the utility of metric based approaches to understanding re-use, sharing, or policy interventions in an open science community are greatly limited by the quality, scope, and reliability of data for these types of analysis.

This also creates a bit of a conundrum because in many ways alternative measures of impact are made possible by practices of open science, but the sharing and pooling of resources across traditional boundaries of intellectual property rights and ownership also renders many quantitative approaches from scientometrics ineffective in measuring the impact of any one resource, organization, or project. The task of what Partha and David have previously called a 'new economics of science' is to better inform policy making through a combination of economic calculations of value according to the efficient allocation of informational resources, with the structural functionalism of sociology, which investigates reward systems, institutions and behavioral norms in knowledge production (1994, p. 487). They argue that in combining these two traditions, science and technology policy might better realize the value proposition of open science, which is impossible to fully grasp through simple measures like a pure cost benefit function or scientometric measure like the h-index. The work presented in this dissertation takes seriously the combination of these two traditions in assigning values to open science work, but (for reasons discussed below) I move away from the structural functionalist tradition of Merton, locating a more useful form of functionalism in the work of Elinor Ostrom's institutional studies.

## Open Science in ICOADS

ICOADS was originally assembled through cooperative exchanges between NOAA, NCAR, and national maritime archives around the world. The early literature describing this work often states that the open accessibility and free cost of ICOADS data was meant to reflect this spirit of cooperation (Slutz et al., 1985). A publication describing the latest release of ICOADS (2.5) reaffirms this in stating, "This is an open community and new participants are welcomed. As part of this involvement, we hope that nations and organisations taking and holding marine surface observations can continue to examine the pathways by which their information is shared" (Woodruff et al., 2011). Part of the challenge to be addressed in my case study of ICOADS is how to combine observations of effective resource allocations made during the DUI study, with the functional aspects of the ICOADS community that was emphasized during the genealogy study.

## 2.3 Collective action

Collective action can be defined simply as, "action taken by multiple people in pursuit of the same goal or collective good" (Oliver & Marwell, 1993). As Parth and David noted in their discussion of a new economics of science 1994, the early collective action work of sociologist Robert K. Merton has been influential to scholars trying to establish an intellectual framework for open science.

In brief, Merton and colleagues were not interested in the content of scientific knowledge, but instead the norms, values and incentives that a culture uses to guard against change, or adapt and evolve to external pressures over time (D. J. Hess, 1997). Merton's work in sociology was therefore concerned with, "...the cultural structure of science, that is with one limited aspect of science as an institution....we shall consider, not the methods of science, but the mores with which they are hedged about" (1973, p. 268).

A key point of Merton's work – and one that is highly contested in contemporary Science and Technology Studies – is that science was positioned as a neutral domain of knowledge production. This privileged status of knowledge was achieved by what Merton claims to be an objective "disinterestedness" of a scientist 1973. From this perspective, the study of social functions in science were to be observed by objective consequences of activities; that is, social functions could not be explained interpretively through subjective dispositions (motivation, incentives, reward structures) (1973, Ch. 13).

This legacy of Merton's functionalism is evident in much of Elinor Ostrom's work on commons and shared governance arrangements 1990. Where the two traditions differ is that Ostrom rejected Merton's notion of subjective and objective consequences of social functions, as well as the idea that any particular domain held a privileged status with respect to rationality or neutrality. Further, in place of society, Ostrom and colleagues were concerned with smaller functional structures; asking instead how an *institution* functioned in light of activities that promote or interfere with the maintenance of a shared physical resource (Aligica & Boettke, 2009). In this context, institutions are to be understood as, "enduring regularities of human action in situations structured by rules, norms, and shared strategies, as well as by the physical world. The rules, norms, and shared strategies are constituted and reconstituted by human interaction in frequently occurring or repetitive situations" (Crawford & Ostrom, 1995, p. 582).

Ostrom's unique approach to functionalism relies upon understanding how purposefully organized groups of people use, share, or pool resources over time, and to what extent the success of these arrangements are governed by informal and formal rules, where rules are defined as, "prescriptions that forbid, permit, or require some action or outcome and the sanctions authorized if the rules are not followed" (Crawford & Ostrom, 1995, as quoted in Imperial & Yandle (2005)). When institutional scholars, following Ostrom's work, dismissed the idea of "objectivity" they replaced Merton's social functions with intended and unintended consequences. What Ostrom and colleagues attempted to understand through their study of rules and shared resources was how externalities (positive or negative) were designed for and managed in institutions for collective action. A concern for both the functioning of institutions over time and the material aspects of collective action makes Ostrom's work especially relevant to contemporary studies of eScience sustainability.

## Collective Action in eScience

Studying collective action in scientific settings, whether it is informed by the work of Merton, Ostrom, or Parth and David's new economics of science, is really to ask a set of questions about cooperation that is central to all of social science, "How do fallible humans come together, create communities and organizations, and make decisions and rules in order to sustain a resource or achieve a desired outcome?" (C. Hess & Ostrom, 2007, p. 42). Information science has long been concerned with the material aspects of this question (M. J. Bates, 1999), including the discoverability, use, and preservation of research products that result from collective actions in science. These information science problems are addressed in this proposal by drawing upon theories of human organization that attempt to explain how "a group of principals can organize themselves voluntarily to retain the residuals of their own efforts" (Ostrom, 1990, p.25). I am particularly interested in how it is that individuals and institutions with overlapping research agendas are able to resolve conflicts, and coordinate their actions to successfully cooperate over long periods of time, with very little government intervention, oversight, and most recently, funding.

## Collective Action in ICOADS

In collective action scenarios, like ICOADS, where the performance or sequencing of activities greatly overlap there is the potential for conflict to arise in how best to achieve a shared goal. Mechanisms for identifying, and solving conflicts between different individuals then becomes paramount to the effective functioning of any given organization that depends upon some form of collective action - and this is especially important to those cooperatives that operate through computer mediated communications (S. M. Easterbrook et al., 1993). This is not to say that conflict is not an important aspect of a highly functioning collaborative project; contemporary studies of conflict show that, for instance, resolving disputes over internet relay chat (IRC) allowed the distributed FLOSS project GNU Enterprise (GNUe) to codify unspoken norms, and create an archive of decision-making that they could refer to in future disputes (Elliott & Scacchi, 2003, similar observations are made in (Coleman, 2005)) .

ICOADS relies on many forms of collective action to curate, develop, or serve its software and data to end users. An especially active area of collective action in ICOADS is related to data quality control and bug reports sent to curators. Part of the value proposition for end users is that although ICOADS data are homogeneous and well described, they are of varying quality and coverage. Understanding limitations in the data such as regions or time periods that suffer from a limited number of observations can be communicated through publications, bug reporting, and email list-servs. Incorporating fixes, or resolving conflicts is often done through a peer-review like process, which makes the "heavyweight" categorization of ICOADS peer production so useful. Further understanding patterns of conflict resolution, and the ways in which the culture of ICOADS functions in these moments is an important aspect of the case study design (described in chapter three).

## 2.4 Commons

In open science the alternative to a private intellectual property regime is a commons-based approach, which provides rules and norms for the governance of resources that "require larger scale utilization than would be efficient in small, individually-owned parcels" (Benkler, 2011a). "Commons" is also a term used loosely by institutional scholars and economists to critique the neoclassical model of property ownership (C. Hess & Ostrom, 2003).

In a commons, the operational structure allowing for access, use, and ownership of a shared resource is distributed amongst the stakeholders of those resources; this can be applied to wholly public goods, or some combination of intellectual property rights for a group and for individual participants, such as a common-pool resource. Increasingly, the legal framework of common property is applied to collections of digital assets that are collectively produced, managed or funded (C. Hess & Ostrom, 2007). A digital environment that distributes work through peer production needs both an intellectual and a legal framework like the commons, as it provides "a coherent alternative model for bringing economic, social, and ethical concerns into greater alignment. It is able to talk about the inalienability of certain resources and the value of protecting community interests. The commons fills a theoretical void by explaining how significant value can be created and sustained outside of the market system." (Bollier, 2007, p. 27).

Some of the most recognizable forms of commons can be found in the shared maintenance of natural resources such as Atlantic Cod fisheries (Hutchings & Myers, 1994), Maine's lobster industry (Acheson, 1988), and livestock grazing pastures (Ostrom et al., 1999). Examples of digital commons include Wikipedia, collections of cultural material like the Hathi Trust, and open source software projects like Apache, Linux, and Android (Benkler, 2011b; Madison et al., 2010)

A heuristic tool for understanding the nature of any commons arrangement is to analyze how a shared resource is able to be accessed, and the rivalry that this access creates amongst its users (Ostrom et al., 1994). To understand rivalry we can ask questions like 'Is there competition for the resource? Is the resource finite, or renewable? Can the resources be simultaneously accessed and owned by two or more individuals?' In the other dimension, we can ask questions about the excludability of a resource, such as 'Can potential users of commons be denied access (either by physical means or on moral grounds)?' Using these two characteristics of a resource we can situate almost any commons arrangement in the following matrix:

Elinor Ostrom's early work on common-pool resources and their governance structures 1990 was the foundation for much of the scholarship that is labeled "commons" including concepts that extended or modified her findings, such as the "anticommons" (Heller, 1998), "semicommons" (H. E. Smith, 2000), "creative commons," "contractually reconstructed commons" (Reichman & Uhlir, 2003), "liberal commons" (Dagan & Heller, 2001), and the "culturally constructed commons" (Madison et al., 2010).

In this proposal my focus is on public goods, where the management of a resource or service has low levels of both rivalry and excludability[1].

[1] Intellectual property laws are meant to encourage the production of public goods by creating legal barriers to copying, distributing and sharing these types of materials. Where appropriate I will discuss intellectual property law, but for the most part I avoid

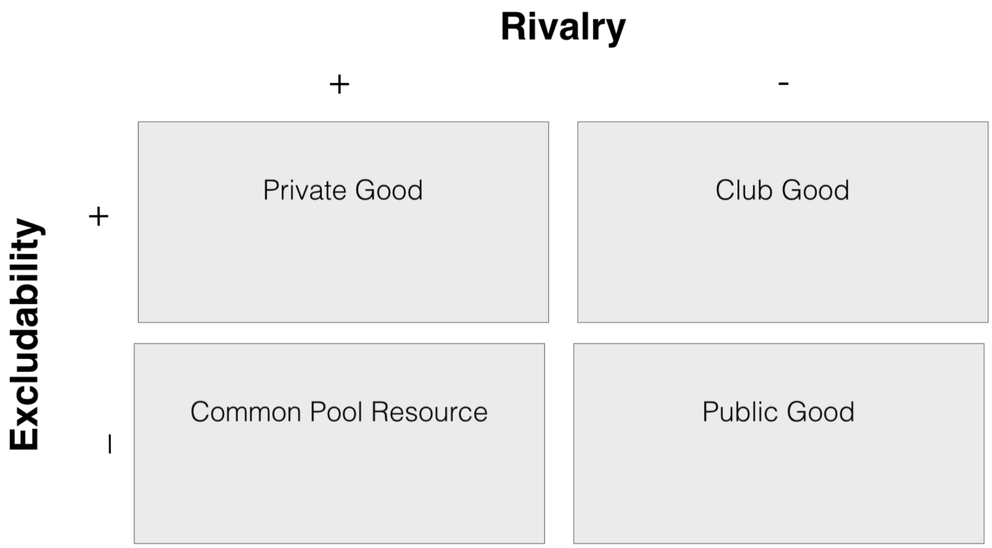


Figure 2.1: Matrix of commons adapted from (Ostrom et al., 1994, p.7)

## Science Commons

A science-based commons is simply a "species of commons dedicated to scientific data and information" (Contreras, 2010), but this label is also applicable to the pooling of software, instruments, and computing resources necessary to effectively conduct research in an open science environment. Similar to a natural resource system, the pooled goods making up a science commons are subject to different forms of competition, and barriers to access. That is to say, data, software and other products of basic science research play different roles within different evidential cultures in which they are produced (H. M. Collins, 1998). It follows then that these products exhibit varying degrees of rivalry and excludability.

Surprisingly, this point is not made more explicit in studies of eScience resource sharing and pooling. Instead, "data" are often assumed to have high degrees of rivalry, and so are either considered to be a private good or a common pool resource. For instance, Birnhotlz and Bietz discuss at length the

discussions of formal laws by focusing on public goods which are to remain in the public sphere, and are therefore governed by informal rules and community norms.

economic principles of “rent extraction” for AIDS researchers who attempt to maximize the return value on their shared data (2003). Birnholtz and Bietz use rent extraction to then describe design implications for systems that will store, and manage “scientific data” more broadly, claiming that these self-interests should be played upon rather than subverted. Similar treatments of research data as a private good or common-pool resource can be found in (Zimmerman, 2008; Faniel & Jacobsen, 2010; Tenopir et al., 2011). This is not to say that any of these studies are wrong in their classification of research data as a rivalrous good, but it is to say generalizing about design requirements or policy implications for “scientific data” from the study of particular sub-cultures or sub-disciplines *is* ineffective. At best, these studies can provide general findings about sharing and resource pooling for goods based on their role within certain commons regimes.

In a science commons, a distinction between rivalry in access and rivalry in use is important to clarify. In some sense, two individuals might both be able to obtain the same set of data from the same commons, but the very fact that two individuals have the data and have the ability to draw similar conclusions does not necessary mean that they will. In the case of ICOADS the “raw” nature of marine climatology data creates a need to further process the data in order to derive any substantive meaning from it. Therefore, mutual ownership does not in any way lessen the value of ICOADS data, software, or other resources. Techniques, software and computing time to do that processing is however exceptionally rivalrous, and is the source of a great deal of competition amongst the community’s participants.

## Science Commons and Public Goods

Although the idea of a science commons and common-property frameworks being applied to digital material is a relatively new phenomenon (Arzberger et al., 2004; Wilbanks & Boyle, 2006; Contreras, 2010) scientific knowledge has long been referred to as a “quasi-public-good” (Fuller, 1993). Callon explains the economic distinction in saying, “The qualification of science as a quasi-public good rather than as a full-fledged public good derives essentially

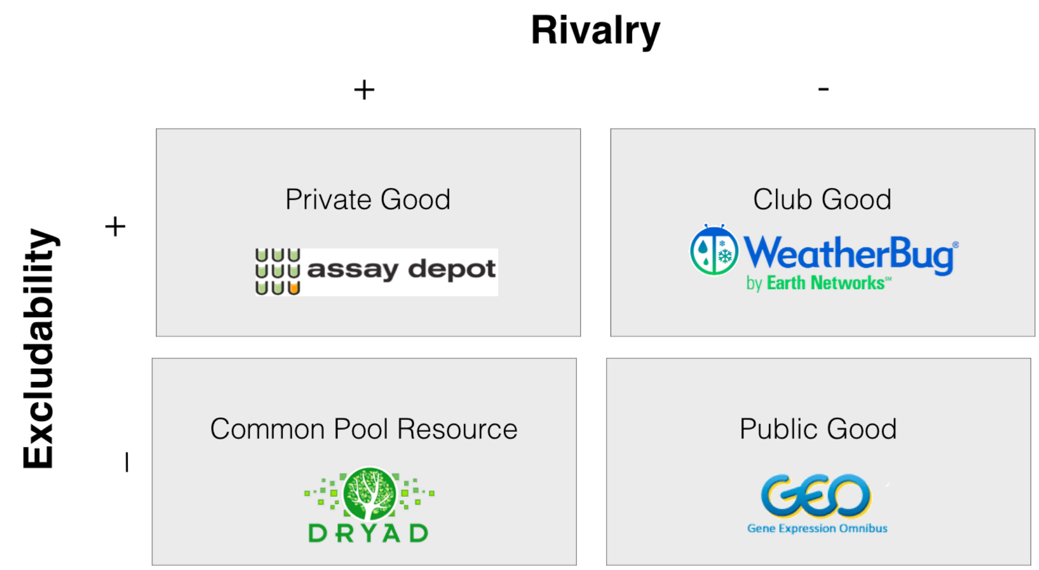


Figure 2.2: Different institutions in the Science Commons according to their rivalry and excludability.

from the fact that it is to a certain degree appropriable-whereas in standard theory a true public good has to be completely inappropriable" (Callon, 1994, p. 400). Increasingly, economists argue for scientific works funded through government subsidies (e.g. journal publications, data, models etc.) to be considered quasi-public-goods for two reasons:

1. Scientific knowledge has certain intrinsic characteristics that make it difficult to exclude access to, and even more difficult to directly commodify. Material products of this enterprise, such as data or software, are the informational carriers of that knowledge, and so restricting use or access is equatable to creating artificial barriers to facts and knowledge[2].

2. Market mechanisms cause businesses to under-invest in basic science research. The government subsidy of scientific research marks it as a good which is publicly funded and should therefore be openly accessible to the public. (Callon, 1994).

The final two sections of this chapter address the problem of free riding that often emerges in public goods settings. This literature provides impor-

[2]This argument very much turns on legal jurisdictions (see Copyright Office, 1998, for USA precedence)

tant background for studying the evolution of commons arrangements.

## 2.5 Tragedy of the Commons, Free Riders & Cooperation

Garret Hardin first coined the phrase "tragedy of the commons" to describe problems of overpopulation 1968. Hardin's argument depends on a hypothetical collective action dilemma from an open grazing pasture. As each individual is concerned with only her/his own well being they are motivated to increase the size of their herd. With no incentive to limit this growth, the size of all herds will swell while the grazing spaces remain the same. This in turn leads to the overgrazing and destruction of the common space:

> Therein is the tragedy. Each man is locked into a system that compels him to increase his herd without limit-in a world that is limited. Ruin is the destination toward which all men rush, each pursuing his own best interest in a society that believes in the freedom of the commons. Freedom in a commons brings ruin to all. (Hardin, 1968, p. 1244).

The tragedy of the commons is an example of what economists have long referred to as the free rider problem. The logic of this idea is explained by Ostrom, "Whenever one person cannot be excluded from the benefits that others provide, each person is motivated not to contribute to the joint effort, but to free-ride on the efforts of others. If all participants choose to free-ride, the collective benefit will not be produced. The temptation to free-ride, however, may dominate the decision process and thus all will end up where no one wanted to be" (Ostrom, 1990, p. 6). Free riding becomes possible when the total benefits from collective action are not a direct result of any one individual's actions. When a group reaches a size where contribution to a common pool becomes difficult to track and group membership is easy to obtain, then the phenomena of free riding can emerge: individual actors may consume or use more than they contribute.

The size function of the free rider problem is often positioned as the most important variable leading to a "tragedy of the commons." Mancur Olson's early economic work on this problem presented the following thesis:

> Unless the number of individuals in a group is quite small, or unless there is coercion or some other special device to make individuals act in their common interest, rational, self-interested individuals will not act to achieve their common or group interests. (1965, p. 2)

Since Olson's writing, Elinor Ostrom and a number of other influential political scientists have demonstrated that while group size is an important variable for sustainable commons arrangements, the devil is in the details; groups large and small often succeed in solving collective action problems through self-governance, and whats more, the logic behind such assumptions about the failure of these arrangements often does not hold up in laboratory simulations, nor real-life scenarios (for an overview see Aligica & Boettke, 2009).

In laboratory settings, Fehr and Schmidt conducted some of the first collective action studies on reciprocity, finding that "economic environment determines whether the fair types or the selfish types dominate equilibrium behavior." (1999, p. 817) or put another way, "contextual factors affect the rate of contribution to public goods" (Ostrom, 2009a) where contextual factors of the economic environment can include the number of players involved, the resources exchanged, and the framing of a scenario. In the latter example, a number of studies have focused on the importance of contextual framing for cooperation to emerge, finding that when participants are told they are playing a "Wall Street" game they produce less cooperative outcomes, but when the same variables are tested using the framing of a "community" game, cooperation is more likely to emerge and be sustained over time (Liberman et al., 2004).

The range of a prisoners dilemma payoff, where b $c$ 0.

| | I Cooperate | I Defect |
|---|---|---|
| **You Cooperate** | b-c | -c |
| **You Defect** | b | 0 |

In his seminal work on the evolution of cooperation, Axelrod first developed probabilistic models to solve the "prisnoers dillema" game. Based on the likelihood of future interaction he was able to show how, "cooperation based on reciprocity can get started in an asocial world, can thrive while interacting with a wide range of other strategies, and can resist invasion once fully established" (Axelrod & Hamilton, 1981). His later work hosted tournaments to solve the "prisoners dilemma" game through algorithms where the most simple strategies were the most effective in creating sustainable cooperation (such as a tit-for-tat reciprocity), and this repeated his early findings that cooperation emerged largely as a function of the likelihood that players would interact in future rounds

The emergence of cooperation in collective action dilemmas has also been studied widely using observational or field-based social science methods. In the early 1980's Acheson studied lobster fisheries in Maine, showing that the temptation to poach or over-harvest lobsters was remedied by a series of nested rules. In this setting some rules were established by gaming and wildlife commissions at the state level, and others at the community (dock) level where "lobster gangs" would enforce social norms through physical intimidation and punishment (1988). During this same period, Ostrom studied long-enduring Spanish Huertas - fertile areas of farm and garden land along riversides- showing that a variety of governance structures could produce highly cooperative outcomes over long periods of time. Ostrom's work focused on how physical attributes of a resource system impacted governance structures. Her work showed that these commons were often sustained through a polycentric[3] governance system where, like Acheson's lobster fisheries, informal rules were nested within formal local and state laws. The huertas offered a particularly valuable look at the commons phenomenon

[3] Polycentricity is rarely discussed outside of political science, but I believe this is a concept that can be exceptionally useful in understanding the functioning of ICOADS and the rules and norms of its governance. Borgman has referred to the overlap in various rules, cultures and policies that impact data sharing as a "conundrum" 2012. The nested rules that apply to ICOADS stakeholders, and how the community adjusts (or does not adjust) to those overlapping rules is a dilemma which polycentric governance theory was meant to help explain.

as these governance systems have been negotiated and renegotiated over a five hundred year period (Ostrom, 1990). Many studies followed Ostrom's seminal work on common-pool resources, some refined the nuances of her design principles (discussed in detail in Chapter 3), others extended her work to socio-economic and socio-ecological resource systems (Folke et al., 2005; Young et al., 2006; Ostrom, 2009b)

Field based research on free riding in commons that are made up of digital resources (including virtual, knowledge, creative, or scientific commons) are rare, but not without precedence. Early work on collaboratories in CSCW produced the idea of a "virtual commons" applied to Usenet - a distributed discussion forum popular on the Internet in the late 1990's. In this work, Kollock and Smith use the design principles generated by Ostrom 1990 to describe how both free riding and cooperation are made easier in computer mediated communication systems, with the effect being a more volatile and dynamic environment for collective action problems to be solved (1996)

A majority of digital commons literature is focused on just two settings (FLOSS and Wikpiedia), but the results from this work are highly valuable for understanding the complexity of the free rider problem in online collaborations more generally. In the FLOSS literature on commons, von Hippel and Krogh studied participation in OSS projects using a case study methodology, noting how free riders were identified and outed in early OSS projects like Fetchmail and Apache (2003). One of their main conclusions is tha:t

> The central deviation we believe that open source software projects display with respect to the assumptions about incentives embedded in the private investment and the collective action models of innovation is that contributions to open source software development are not pure public goods –they have significant private elements even after the contribution has been freely revealed (Hippel & Krogh, 2003, p. 16).

In other words, traditional notions of free riding in public goods regimes aren't wholly applicable to the OSS environment, because the spillover (externalities) of participating in the production of the software is where novel sources of value can be located. So even if the software is a pure public good the value proposition of an OSS project is a blend of private and public benefits.

Much of the early work on Wikipedia as a commons platform focused on the design of a governance model that could simultaneously attract new participants and sustain existing contributors (i.e. Nov, 2007). Interestingly, free riding on Wikipedia is assumed to be pervasive because there are many more visitors (readers) of the site than there are registered or active contributors (editors). Antin and Cheshire's work shows that a majority of readers have incomplete information about how to edit articles, and low confidence in their ability to correctly use MediaWiki editing software (2010). They conclude that the idea of free riding, in the sense that readers are taking advantage of others work without reciprocating, is more nuanced in the Wikipedia environment. From a design standpoint they argue that the task is not in motivating readers to edit immediately, but in finding intermediate steps for participation such as viewing page-history or talk-pages to become familiar with the culture of editing content on wikipedia.

Antin and Cheshire's work provides a subtle, yet important example of identifying and categorizing free riding for my proposed case study; there are many more users of ICOADS than there are contributors. ICOADS has recently introduced new ways for users to report errors and share data (S. R. Smith et al., 2014). Antin and Cheshire's work provides a helpful example of how to observe participation, contribution, and variations of the the free rider beyond the level of a user's directly measurable participation.

## ICOADS Context

This dissertation focuses on a culture that produces, uses, and develops resources that are quasi-public-goods because they are managed with relatively low degrees of exclusivity (i.e. not many people can be excluded from obtaining the software or data) and as a result of their digital form they are not subject to a high degree of rivalry (i.e. your having a copy of this dataset does not preclude my having a copy). What makes ICOADS a unique and highly important case for understanding the future evolution of institutions for collective action is that the management of these resources as public goods is not regulated by a federal government mandate, nor is it a response to some marketplace pricing signal. ICOADS is a self organizing institution that has persisted for many years by arranging its production in a commons-based peer production model. However, ICOADS is also facing a funding shortage, and will face a number of obstacles in sustaining its commons arrangement in the future. A substantive question to be addressed in this research is how ICOADS continues to solve resource allocation problems necessary to sustain an open-science, commons-based model of peer production.

# CHAPTER 3

## Introduction

*In chapter three I first describe a range of research methods that can be used to study peer-produced commons, collective action, and sustainability. I begin first by explaining how this work will overcome limitations with the case study approach. I then describe the design and procedure for a case study of ICOADS, and how it will be used to test a proposed framework. At the end of this chapter, I describe the overall contribution of this research, and a schedule of completion.*

## 3.1 Empirical Social Science

Conducting empirical research in the social sciences is often a trade-off between some combination of available time, money, skills, and material resources - each presenting a choice between one way of collecting or analyzing data and a number of alternatives. Generically, we can situate trade-offs between data collection and analysis in a two dimensional matrix; in one dimension we can place the choice of an empirical research method, and in another dimension we can place the use of a theoretical descriptive technique.

The choice between different approaches to empirical research presents a trade-off between"dirty" or "clean" methods (P. J. Boettke, 2000). Clean empirical methods are characterized by narrowly scoped research questions, ordered and systematic data collection, and depend upon well established thresholds of significance for the acceptance or rejection of a research result. Dirty empirical research methods are, inversely, characterized by broad re-

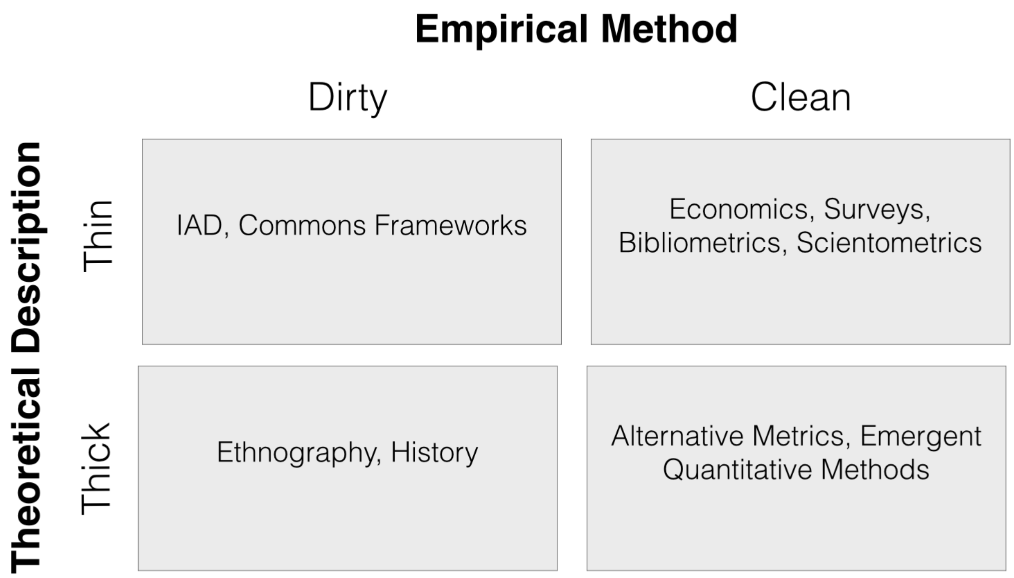


Figure 3.1: Matrix of Social Science Research (adapted from P. J. Boettke, 2000)

search questions, opportunistic and informal data collection, and the use of subjective judgment about the relevance of a research finding.

The other dimension of this matrix presents a trade-off between theories used to analyze a research finding, and can be characterized as producing either a “thin” or “thick” set of descriptions. Thin theoretical descriptions often take the form of a framework that can make the content of an explanation easily accessible to the reader. Thin descriptions might use a narrowly defined theory to explain research findings, or a set of “most likely” explanations applied to selected research results. Thick descriptions often include a set of emergent theories about the situated context in which some thing obtains meaning, or value.

On the one hand thin descriptions lack depth in explaining the broader context of a phenomenon being studied, and are not often concerned with the “how and why.’ On the other hand, thick descriptions offer rich but dense and non-linear narratives that are open to many interpretations.

## Thick & Dirty; Thin & Clean

At the intersection of these two dimensions – dirty and clean, and thick and thin- is where we can locate most social science research projects.

To return to research projects described chapter two, Vertesi and Dourish's study of "data economies" is an empirically dirty and descriptively thick study of value. The authors present in rich detail the different strategies and motivations for sharing data among two research teams working at NASA's Jet Propulsion Laboratory (2011). The results of this work take the form of broad "implications" for the design of a future data management system.

Bollen, Fox and Singhal conducted a study of the benefits of supercomputer access to TeraGrid researchers is an empirically clean and descriptively thin research project, answering questions like, "Do mostly high-impact scientists benefit from the TeraGrid?" or "Are some scientific domains more strongly represented than others in TeraGrid-supported work?" (2011). The authors use highly normalized and openly accessible citation data, and the findings are validated by established statistical tests. While these results offer easily digestible "proof" that the scientist's using the TeraGrid infrastructure have produced papers with high citation rates, the author's thin description of this phenomenon offers few details about how, or why the TeraGrid publications have had an impact on the geoscience research community. As they state, "TeraGrid usage is indeed significantly correlated with the scientific impact of its users, but the causal direction of this relation remains unclear" (Bollen et al., 2011, p. 11)

## Thick & Clean; Thin & Dirty

While the two approaches described above are well established modes of inquiry for social science research, research projects that populate the opposite cells of this matrix are more rare. Some descriptively thick and empirically clean research can be characterized as a "kitchen sink" approach where every possible statistical test is thrown at a dataset to see what might emerge from the results (P. Boettke, 2000).

With increased access to data and open-source "plug and play" software tools the descriptively thick and empirically clean research approach is becoming more common. Topic modeling projects in the digital humanities (Rosen-Zvi et al., 2010), social network analysis and data mining in computational social science (Keegan et al., 2010), and the visualization of sentiment analysis in studies of social media use (Hochman & Schwartz, 2012) are all salient examples of research that is descriptively thick and empirically clean.

In the opposite cell, descriptively thin and empirically dirty research would ask broad research questions about diverse subjects and use research methods such as participant interviews or ethnographic methods which are impossible to reproduce. These types of research projects would then generate highly structured descriptions by using the conventions of a previously developed framework – producing thin descriptions of a phenomenon by abstracting from the messiness of an empirically dirty method. As an example, the Institutional Analysis and Development (IAD) framework achieves this by asking broad research questions, like "What motivates fishermen to cooperate with one another in sustaining a fishery" (Hutchings & Myers, 1994) and uses field-based research methods such as participant observation, interviews, and surveys to gather behavioral data about individual stakeholders. Researchers using the IAD are then guided by a well-established framework that categorizes and organizes the data for analysis. There may seem to be a high investment for a small payoff in the descriptively thin and empirically dirty approach, but this mode of inquiry also presents a way to overcome the n = 1 shallowness of a case study. Results fitting into a structured form of analysis makes it possible for the n= 1 formula to actually become an n = X + 1 where X represents an archive of comparable studies.

## Research in This Dissertation

The studies presented in chapter one both used empirically clean research methods, but differed in the presentation and interpretation of their respective research results. In the Data Usage Index we used data which were publicly available and a set of adapted, but well accepted measures of impact (Weber, Thomer, Mayernik, et al., 2013). Consequently the description of our results were thin in reporting quantitative scores across a variety of data products with little ability to interpret their broader contextual meaning. The genealogical study of ICOADS also used publicly available data and well accepted techniques from evolutionary biology for our analysis (Thomer & Weber, 2014). In that the application of those techniques were novel our descriptions of the results were broad, highly subjective, and our description was thick.

The case study in this dissertation will be a quintessentially thick and dirty research project, with all of the benefits and drawbacks of an n=1 study as described above. My argument from chapter one is that by over relying on this mode of inquiry in studying eScience collaboration and resource sharing, social science is failing to adequately inform federal science and technology policy (Jackson et al., 2013). The contribution this dissertation will make is creating a framework that can turn the n = 1 shallowness of the case study approach to developing theory, into the n = X + 1 power of an analytical framework. This will be done by first analyzing relevant features from four existing frameworks, and fitting the findings of the case study data to these features using an iterative process. This work has initially built off of existing efforts to extend the IAD framework to cultural commons settings (**?**, e.g.).

In the following sections I describe the design and protocol for completing a case study of ICOADS. This case study will shed light on the complexity of this particular project, and demonstrate the need to develop a framework for studying similar cases. I then describe a parallel process for using the data from the case study to develop a framework which can help identify important, emergent properties in these settings. Again, the goal of this work is to develop a diagnostic tool which can be used to conduct multi-method social science work in collective action settings.

## 3.2 Case Study

The case study approach is not so much a method as it is a comprehensive research strategy (Yin, 2003, p. 14). The marked features of a case study are that it:

- Investigates a contemporary phenomenon within its real-life context
- Is appropriate when the boundaries between phenomenon and context are not clearly evident
- Copes with the technically distinctive situation in which there will be many more variables of interest than data points
- Relies on multiple sources of evidence, with data needing to converge in a triangulating fashion
- Benefits from the prior development of theoretical propositions to guide data collection and analysis (Quoted from Yin, 2014).

The collective action problems and dilemmas addressed in this proposal draw upon theories of human organization that attempt to explain how "a group of principals can organize themselves voluntarily to retain the residuals of their own efforts" (1990, p. 25), and more specifically how it is that individuals and institutions with overlapping research agendas are able to resolve these conflicts, and coordinate their actions to successfully cooperate over long periods of time.

In social science research that takes things like organizations, institutions or systems as a unit of analysis, the case study approach can be used either to test, extend, or further develop existing theories (Stake, 1995). A case study aproach can also act as the operational strategy for putting an existing methodological framework into action. In the latter sense, a case study sets out a design for collecting data based on specific questions to be answered by a specific case. The case study will identify variables in a framework to decide what is to be studied, how a method will be used to find out what is asked of or about the specific context of these variables, and how the gathered data will be linked to the categories of the framework for analysis.

A case study, like a framework, can mean different things to different fields engaged in social science research. Yin identifies three types of case studies:

1. Exploratory - often experimental, and aimed at developing or refining a general thesis. The exploratory case study is valuable for investigations which are emergent, or where little research is available to support existing theories.

2. Descriptive - often uncovers phenomena that are not well understood, or oversimplified. The descriptive case study is important in clarifying how a well accepted theory, such as social deviance (H. S. Becker, 1967) applies to a new environment (i.e. social networking sites).
3. Explanatory - seeks to make meaning of an event, policy, or period -asking why it occurred, how it was resolved or what outcomes mean for contemporary (or future) settings (2003)

A fourth type of case study that is related to both the descriptive and exploratory is the critical or paradigmatic case study. The critical case study identifies a single case that is exemplary in some way, such as a medical oddity that is rare, a revolutionary social movement, or as was explored by Kuhn evidence of some larger pattern that could only be supported by the in-depth study of an exemplary case (Kuhn, 1962; Flyvbjerg, 2006). I earlier argued that we can see ICOADS as a kind of sociotechnical system that will become more prevalent in the coming years. This is a result of shrinking federal support for basic science research and consequently the need to pool shared resources, but also more practically as the type of institutional arrangement needed to tackle grand challenge science problems. My case study of ICOADS is most comparable to the critical case study, but takes on many characteristics of the explanatory model.

## Research Design

Case study research design requires the following:

1. A study's questions

2. Propositions
3. Unit(s) of analysis
4. Logic linking the data to the propositions
5. Criteria for interpreting the findings (Yin, 2003).

In the following sections I describe my design of a critical case study for ICOADS using these five components.

Research questions

The research questions this case study will address are:
**RQ1** : How does ICOADS, as an institution for collective action, overcome transaction costs in organizing its production of new knowledge? If peer production is indeed the model by which this is achieved:

> **RQ 1.1** How, and/or in what ways does it differ form other forms of peer production?
>
> **RQ 1.2** How does ICOADS sustain these successful cooperative arrangements
>
> **RQ 1.3** What are the activities of its community members necessary to achieve this sustained success, and how can those actions be recognized, either formally or informally, over the duration of the project's existence?

**RQ2.** How has ICOADS, as a project with particular governance arrangements, evolved in response to external pressures from funding agencies, the politicization of climate related research, and rapid technological change?

Both of these questions are answered in the context of events occurring after the 2012 defunding of NOAA's Earth Systems Research Laboratory, but the examination of how these events are similar to or different from historical ones are necessarily important to interpreting the findings of this work. That is to say, while case studies are typically concerned with "contemporary phenomena" they are of limited value unless they are able to answer these questions in a broader historical context. Diane Vaunghn's work on NASA's *Challenger* and *Columbia* accidents is an exemplar for this type of case study

(1996; 1999). Her analysis is grounded in contemporary events, but through archival work she necessarily reflects on the organizational and institutional factors that led to the present. Vaughn describes this process as historical ethnography (Vaughan, 2006).

Propositions

Propositions stated in a case study are usually some combination of a priori and a posteriori knowledge about the unit of analysis, the context or setting in which a subject will be studied, and the research questions that will be asked of those settings. My work with the ICOADS community in developing the DUI and Genealogy of ICOADS data led to generating research questions about the evolution of cooperation, and the sustainability of collective action in this environment. In chapter two I defined and gave examples of research applicable to ICOADS, and this in turn helped me generate the following set of propositions:

- ICOADS is a peer produced resource. As such, it has qualities that are similar to commons-based peer production systems that follow a heavyweight model.
- However, ICOADS contributors and users largely consist of experts, and it therefore diverges in important ways from traditional peer production models that loosely coordinate non-experts.
- Changes in any one of the technical, social, political, or economic aspects of ICOADS partners will impact broader peer production arrangements, and the project's overall ability to solve collective action problems.
- These changes will impact participants differently (benefiting some, harming others).
- Solutions to collective action problems adopted by ICOADS will be similar to those found in Ostrom's study of common-pool resources.
- In particular, the concept of polycentricity will play an important role in how institutional arrangements evolve.
- However, effective solutions for collective action will look different than

common-pool resources like Spanish Huertas (Ostrom, 1990), and Open Source Software projects (Schweick and English, 2012) as a result of ICOADS being made up of quasi-public-goods.

### Unit of Analysis

In short, a unit of analysis is the subject of a case study (Long, 2004). A related but distinct concept is the unit of observation, which is often a manifestation of the subject being analyzed. To return to an example used earlier in this chapter, Vertesi and Dourish's study at NASA's JPL used "data sharing between mission teams" as a unit of analysis, and individual teams and team members as units of observation. Case study research also draws a distinction between holistic (single unit of analysis) and embedded (multiple units of analysis) (Yin, 2003, p. 40)

The case study design for this dissertation is a single-case (ICOADS) with a single unit of analysis (cooperation in solving collective action problems between project partners) and multiple units of observation, including digital resources (ICOADS software and data) and curators, users and stakeholders of the ICOADS project.

### Data collection method

The mode of inquiry I've used during the two years of engagement with the ICOADS community has been influenced by ethnomethodology as found in cultural anthropology (e.g. Garfinkel, 1967) and science and technology studies (e.g. Lynch, 1997), but it is most directly informed by Harry Collins' work on "participant comprehension" (1987). In studying the material culture of gravitational wave physics, Collins described this method as "an interpretation of participant observation under which the field-worker tries to acquire as high a degree of native competence as possible and interaction is maximized without worrying about disturbing the field site" (1998, p. 297). Collins' motivation for developing this method is in pursuit of an "interactional expertise", or a third kind of knowledge that sits between formal / propositional knowledge and informal / tacit knowledge (2004, p. 125-7).

Collins' argument is that during his time studying gravitational wave physics he was able to achieve an expertise which was something different than the kind that comes with formally studying and being a part of a discipline as a practitioner. Through linguistic socialization, traditional ethnographic observation, and extended field work Collins could read, participate in discussions, and defend his arguments about physics without having the ability to actually do the physics himself. Similarly, Anthony Giddens has described a similar mode of work, saying "I have accepted that it is right to say that the condition of generating descriptions of social activity is being able in principle to participate in it. It involves 'mutual knowledge,' shared by observer and participants whose action constitutes and reconstitutes the social world" (Giddens & Dallmayr, 1982, p. 15).

My time working with and studying ICOADS has allowed me to develop something like a "mutual knowledge" or an "interactional expertise" in that I understand the limitations and uses of ICOADS software and data in ways that allow me to converse with its community, to read, comprehend and participate in discussions of its literature, and most importantly to argue - a crucial point of linguistic socialization (H. M. Collins, 1998)- with one or more of the conflicting theories in the field of marine climatology. I've even given an invited talk at a biennial marine climatology meeting, which is the major professional conference for the ICOADS community (Weber et al., 2014).

My use of"participant comprehension" expands on Collins method by conceiving of participants more broadly. That is to say, my "field-site" is not simply a series of laboratories, offices or even people. I locate my phenomena of interest (sustainability of collective action) mostly in digital environments: the logs of data repositories, the encoding standards of ICOADS, and the many engineered institutions and artifacts that make up this cooperative. Like Collins, my interaction is "maximized" by informally interviewing, talking with, and observing people who produce and use ICOADS; but, I also interact with and investigate ICOADS by using it's various forms, visualizations and software. I generate questions to investigate not only through the "linguistic socialization" that Collins describes (H. M. Collins, 1998), but also through a kind of "material socialization" by both using ICOADS myself, and studying it in different formal and informal environments of use.

The questions, and categories that have driven this work are the outline of a a framework, borrowed and adapted from multiple existing frameworks that I review in the second half of this chapter. Further details on the methods and data collection techniques can be found in Appendix A.

### Linking Data to Propositions and Interpreting Findings

Without formal methods for determining the truth value of a proposition, or the statistical significance of a finding case study research depends on inductive data analysis techniques such as triangulation (Denzin & Lincoln, 2008, p. 133), pattern matching, and a "replication logic" (Eisenhardt & Graebner, 2007). Undoubtedly the major critique of case study research is that this step is performed too casually resulting in underdeveloped theory or thin explanations of a phenomena (Flyvbjerg, 2006). Case study research can guard against this critique by using various forms of data validation, including:

- **Construct Validity**: Requires the careful selection of a case, a unit of analysis, using multiple sources of evidence, and selecting key informants that are willing to read the work being produced
- **Internal Validity**: Is largely applicable to causal explanations, and requires intensive pattern matching, repeated findings across cases, building a logic model, and addressing rival explanations in answering a set of propositions.
- **External Validity**: Concerns the generalizability of the findings, and the extent to which they are representative of a phenomenon in different contexts. In single cases, external validity is addressed through the use of theory, and comparing or contrasting the support of that theory with the explanations produced from a case study.

- **Reliability**: Deals with the repeatability (not replication) of a case study. This is addressed thorough documentation, and a well developed protocol (Yin, 2003).

At this stage of my research, I can only address issues of construct validity and reliability. For the former I have relied on a key informant at NCAR who has collaborated with me on both studies presented in chapter one, introduced me to members of the ICOADS community for interviewing, and provided me with archival material for historical portions of this work. He has agreed to read and provide feedback on future iterations of this dissertation. For reliability, I have modified a protocol developed and tested in previous work (Weber & Palmer, 2014). This protocol outlines how data are to be recorded, coded, stored and managed. Details of the protocol can be found in Appendix A.

Progress on Case Study to Date

As of August 01, 2014 I have completed a total of 15 months in residency at NCAR, working with software engineers and the director of the RDA. This time has included data gathering as both an observer and a participant in ICOADS curation. I have completed 7 informal interviews - including developers (n=4) scientists (n=2) and an employee of the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) (n=1).

I have participated in four conferences related to ICOADS research and development, as well as a workshop for the design and planning of an ICOADS Value-added Database (IVAD). During these sessions I recorded field notes following methods from Emerson, Fretz and Shaw (2011) on ethnographic fieldwork. These data are further condensed to memos that will be used to test portions of the framework described in the next section.

There are a number of limitations of the data that I've collected for the case study thus far. In particular, I need to gain a better understanding of ICOADS from end-users (not people directly funded to work on or develop ICOADS). To date my interactions with the ICOADS community outside of

NCAR has been opportunistic and based on who has attended major conferences / workshops or who is connected to ICOADS through my key informant at NCAR. Over the next four months I plan to continue collecting data by participating in IVAD's planning (teleconference calls), as well as interviewing a broader range of ICOADS stakeholders. I will prioritize individuals who are not directly related to NCAR or NOAA, with a target of conducting five additional interviews.

### Outcomes and Contribution of Case Study

A chapter of this dissertation will be devoted to findings from this case study. I will use the propositions that I've stated to frame this work, showing how or why they were supported by my interactions with the ICOADS community. The analysis of events occurring after the 2012 defunding event will be the major focus of this work. In abstracting from the propositions to the research questions I will directly address how ICOADS as an institution for collective action overcame these issues, and the ways that this related to how peer-production systems evolve in the face of conflict. These events will be historically contextualized using the reflection of my participants and archival material relating to ICOADS, as well as literature that I reviewed in chapter two.

Data gathered during the case study will also be used to develop a framework, as described below.

## 3.3 Framework

In chapter one I argued that if science and technology policy is to move beyond simple panaceas for solving the complex interrelated problems of sustaining sociotechnical systems then an analytical framework is needed to address interactions between different types of variables (resources, users, technologies) and different levels of institutional interaction (disciplinary, organizational, funding agency, etc.)

My third research question is about how existing frameworks can be adapted for these purposes.

> **RQ3**: How can analytical frameworks successful for studying collective action problems in other domains be modified for sociotechnical settings where issues of sustainability, cooperation and shared resource management are diverse and shifting over time?

In this section I will define the differences between frameworks, theories and models in social science research related to institutions and organizations. I will then describe the process I've used thus far to analyze existing frameworks, and a preliminary draft of a new framework. I'll conclude with the future steps necessary to complete the framework and a schedule for completion.

## Frameworks, Theories, and Models

A **Framework** can mean different things to different fields engaged in social science work. For the sake of this dissertation, "Frameworks provide a meta-theoretical language that can be used to compare theories. They attempt to identify the universal elements that any theory relevant to the same kind of phenomena needs to include" (Ostrom, 2011, p. 8).

**Theories** posit general causal relationships among some subset of these variables or categories of factors, designating some types of factors as especially important and others as less critical for explanatory purposes. Theories are used to focus in on one more parts of a framework in order to 'diagnose a phenomenon, explain its processes, or predict its outcomes..." (Ostrom, 1990; McGinnis, 2011, p. 28-9). I take theories to have different kinds of powers – descriptive; rhetorical; inferential; as well as having different forms of application (Halverson, 2002). Each of these powers are emphasized or demoted based on the systematic gathering of data that a framework enables. Some frameworks are good at testing and comparing theories that are inferential, and others are good at generating useful descriptions.

**Models** specify the "specific functional relationships among particular variables or indicators that are hypothesized to operate in some well-defined set of conditions"(McGinnis, 2011). In a sense, models put theories to work. Models are not exact simulations of reality, but always a simplification of some larger complex system. When used in a sociotechnical setting models are useful for understanding or demonstrating the consequences of policy decisions (Easterbrook, 2014). In some cases a simplification is helpful to understand basic causal relationships, and in other situations models can prove valuable for predicting or modeling a given outcome.

This dissertation will develop a **framework** for analyzing peer production arrangements, their sustainability, and their processes for solving collective action problems that arise from the pooling and sharing of research objects over time. The framework will provide a consistent vocabulary for important variables and their roles in a peer production process (resources, users, technologies) as well as different levels of institutional interactions (disciplinary, organizational, funding agency, etc.). I describe this process in detail in the following section.

## 3.4 Stepwise Development of Framework

The development of a framework to support the analysis of sustainability will be done using a stepwise process that adds concepts, variables or levels of interaction as necessary, and decreases the number of overlaps where possible. My work on this development process includes the following (non-sequential) steps:

1. Analyze a set of pre-existing frameworks for features relevant to sustainability, longitudinal analysis, sociotechnical systems, peer production and common property regimes. The initial analysis of these frameworks can be found in Appendix B.

2. Incorporate relevant features from this analysis into a preliminary set of questions to be addressed in gathering case study data (below).

3. Identify relevant concepts from systems theory literature, which provides a domain ontology to capture concepts like stocks and flows, balancing and feedback loops, and emergent behaviors in dealing with complexity in built or engineered environments (Weinberg, 1975; S. Easterbrook, 2014).

4. Develop new categories not found in existing frameworks.

5. Identify the different levels of analysis necessary for a sustainability framework (policy relevant levels, operational levels, etc)[1].

As a brief demonstration of this process, I can explain a portion of my preliminary work as follows:

- I began by analyzing four frameworks: the Institutional Analysis and Development framework from Ostrom and McGinnis; the Constructed Cultural Commons framework by Madisson, Frischmann and Strandburg; the Sociotechnical Interaction Network framework by Kling, McKim and King; and the Multi-dimensional In-depth Longitudinal Case Study framework by Schneiderman and Plaisant.

- Using the highest level categories from the IAD (McGinnis, 2011) I outlined what each category was trying to achieve in studying a socio-ecological system.

- I then identified what was similar and was different about ICOADS as a sociotechnical system (i.e. ICOADS is an engineered system, not a naturally occurring huerta)

- Most studies of a socio-ecological system using the IAD had the following features.

    1. The boundaries between resources were clear.

[1]Identifying different "levels" of systems analysis is sometimes referred to as a process of "boundary critique" in complexity theory (e.g. Midgley et al., 1998)

2. The resource systems studied were relatively small, well bounded, and easy to observe.
3. Overcoming collective action problems was immediately important to some aspect of the community's existence (water, food, shelter, etc.)
4. The institutions for collective action were relatively long-enduring and had evolved over time.
5. The ability to spend time in the field observing, or interviewing was available and relatively unobtrusive (Quoted from Ostrom, 2011).

Each of these assumptions is complicated, if not completely opposite for peer produced commons of digital material:

1. Boundaries are unclear
2. While access to resources are important to efficient research, alternative means of access do exist (this became clear during the federal government shutdown of 2013 when many NOAA scientists started to access ICOADS data from NCAR)
3. Resource systems are large, distributed across many different platforms.
4. Institutions are rapidly evolving and often short-lived or unrecognizable from one project to the next (i.e. a code base exchanged between projects).
5. Due to the size and nature of collaborations (virtual), traditional observation techniques are not possible.

To account for these differences I changed the first level of analysis of the IAD from 'Exogeneous Biophysical Characteristics' to 'Sociotechnical Contexts.' This level of analysis for my framework includes questions about the type of good produced (public, private, common-pool, etc), and questions about the significant properties of the good. These are meant to deal with problems of boundaries that exist between different types of goods. Below is the first draft of the framework that I have developed. Following this draft is a section that describes the process for completing the framework development.

# Preliminary Design of Framework

*Current categories include sociotechnical contexts, actions and actors, and outcomes and evaluations. I describe each section in detail below.*

## Sociotechnical Contexts

### Resource Characteristic

**Type of Good**: Is the resource managed as a private, public, or club good? To what degree is there rivalry for the resource? Are there barriers to access and use? How are barriers enforced?

**Significant Properties**: (Traditional software significant property categories are content, context, rendering, structure, and behavior) What does the resource consist of? What platforms or systems is it used on? What are the standards to describe, encode, or archive this good? What are its known dependencies, and howhave these evolved over time? Does the resource exist in many locations? Many versions? What are the salient differences among these versions?

### Attributes of Community

**Reciprocity:** Do members of this community share the common expectation that others will tend to reciprocate their own acts of cooperation? How, and to what extent? (McGinnis, 2011)

**Trust:** Do members of community exhibit reciprocity ? Is this reflected in citation analysis or other formal methods of acknowledgement? How do members describe goods in terms of quality, reliability, care, etc.?

**Common Understanding (or shared understanding):** What values and conceptual frameworks do the members of this community share, and specifically do most of them share at least some core values or goals as a member of that community? How are the commonalities expressed? Is there documentation of expectations? Memorandums of understanding? Is there a license that is attached to goods stating these expectations about fair use. etc.?

**Social Capital:** This can be studied by analyzing the resources that an individual can access, and their understanding or belief that they can obtain goods that are not within their immediate network. Can also be studied with a survey that asks participants to report knowledge of certain resources and ability to access or obtain others (i.e. Appel et al., 2014)

**CulturalRepertoire:** What are the set of strategies, norms, rules, organizational templates, and other remembered or imagined practices that are readily available to the members of that community for their use in processes of deliberation and implementation? (McGinnis, 2011)

### Rules in Use:

**Formal Rules:** To what extent are rules codified in a formal document, mission statement or memorandum of understanding? Do community members refer to these documents? Where are these documents stored, made available to new members, and referred to when conflicts arise?

**Strategies for Deviance:** What are the norms or rules being used on a regular basis by participants that diverge from or mirror the formal rules?

## Actions + Actors

### Action Situation

This is essentially the unit of analysis for applying a framework. The questions to be answered then are about how actors (broadly construed) observe information, select actions, engage in patterns of interaction, and realize outcomes from their interactions.

## Actors

The term actor here is broadly construed as both human agents and software agents. The reasons should not be confused with anthropomorphism, but instead how a community conceives of and attributes action with respect to the sustainability of a resource. The inspiration for this treatment is Callon's study of networks of translation between fisherman, scientists, consumers and scallops where he noted that in his unit of analysis (the network) a difference between intentional and unintintentional action did not matter, "The only thing that counts is the definition of their [scallops] conduct by the various actors identified. The scallops are deemed to attach themselves [to certain types of breeding grounds] just as fishermen are deemed to follow their short term economic interests. They therefore act." (Callon, 1986, p. 25, bracketed content was added by me for sake of clarification). In ICOADS case, data processing algorithms, floating buoys, satellites, models of physical systems, and software act in the same way that scientists, curators and funding agents do. The questions to answer about actors then are not whether or not they act intentionally, but instead who or what has agency?

## Outcomes and Evaluation

### Outcomes

The outcomes of action scenarios can take many different forms. For the sake of this dissertation, which is concerned with the sustainability of collective action, I evaluate outcomes based on the evaluative criteria discussed below. These will need to be adjusted in many different settings (McGinnis, 2011)

Evaluation

Six forms of an outcome are identified as the efficiency, equity, legitimacy, and fiscal equivalence of an action situation (McGinnis, 2011).

**Efficiency** in use of resources, especially capture of economies of scale.

**Equity** in distributional outcomes and processes.

**Legitimacy** as seen by participants in decision processes (participation tends to increase legitimacy)

**Accountability** especially to direct users of resource.

**Fiscal equivalence:** the extent to which the beneficiaries of a public good or service are expected to contribute towards its production.

**Consistency** with the moral values prevalent in that community.

## 3.5 Completion of Framework

The steps taken to finish the framework will be similar to that of other inductive approaches that depend on an itterative process of making sense of data, fitting explanations to abstract categories, and reaching a point of saturation in explaining the phenomena under study (Suddaby, 2006). In the completed dissertation each category will be defined, and an example from ICOADS will be used to demonstrate their significance. Where possible, I will relate this to relevant literature or my own previously published work in order to demonstrate the ability of the framework to accommodate different eScience contexts.

## 3.6 Limitations of Proposed Study

There are a number of limitations to the study I am proposing. In the case study, I have had a limited set of interactions with a large and diverse international project. I have attempted to guard against this limitation by attending international conferences related to ICOADS, and in interacting with visiting scholars at NCAR.

Although I've developed a high competency in this field, I nonetheless have an incomplete understanding of marine climatology and climate science more generally.

During my time interacting with participants, I did not record my interviews. This decision was made to be least disruptive and most natural to the community I was collaborating with, and my own reluctance to ask a group of individuals whose work is highly politicized to be tape-recorded.

All single-case study work suffers from a lack of generalizablity. The protocol that I have developed and the validity measures described above will be important for assuring a rigorous and empirical study is conducted, but the results from this work will still be limited in their scope of the sustainability and collective action problems facing eScience.

An important aspect that I will have to address in the completed dissertation is how and to what extent this framework is adaptable to a broader research community. It may be that portions are very succesful and others are not (i.e. What can this framework achieve with respect to different levels of intraction that something like Weinburg's 'principles of complimentarity' cannot? (1975).

## 3.7 Timeline for Completion

| | | Aug. 2014 - Feb. 2015 | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Aug | Sept | Oct | Nov | Dec | Jan | Feb |
| **Case Study** | Complete Data Collection | | | | | | | |
| | Data Analysis | | | | | | | |
| | Written Narrative of Findings | | | | | | | |
| **Framework Development** | Comparison of Frameworks | | | | | | | |
| | First Draft of Framework | | | | | | | |
| | Final Version of Framework | | | | | | | |
| **Completed Dissertation** | First Draft to Committee | | | | | | | |
| | Final Draft | | | | | | | |
| | Proposal Defense | | | | | | | |

## .1 Appendix A

08/12/2104 - this content will be added to subsequent drafts, deposited at: http://bit.ly/1ropvH6

## .2 Appendix B

*In this Appendix are an initial analysis of four frameworks: the Institutional Analysis and Development framework from Elinor Ostrom; the Constructed Cultural Commons framework by Madison, Frischmann and Strandburg, the Sociotechnical Interaction Network by Kling, McKim and King, and the Multi-dimensional In-depth Longitudinal Case Study framework by Schneiderman and Plaisant.*

### The IAD

In the late 1980's, the Bloomington school began to develop a more formal framework for studying the evolution and function of commons. The Institutional Analysis and Development (IAD) framework was to guide the analysis of data collected through many different empirical methods. Various versions of this framework can be found in the work of Kiser and Ostrom (2000), Ostrom (1990), Ostrom, Gardner, and Walker ostrom1994rules, and McGinnis (2011). The settings for much of this work were institutions that operated with a mix of governance structures, and had a need for longevity or sustainability of a single shared resource. Initially the IAD was designed as method-agnostic tool that could "simplify the analytical task confronting anyone trying to understand institutions in their full complexity." (2011).

Another goal of this unifying framework was to integrate the work of sociologists, lawyers, politicians, economists, and political scientists in trying to understand how "institutions affect the incentives confronting individuals and their resultant behavior" (Ostrom, 2009b). While the original goal may have been to simplify the task of studying institutions in diverse settings, the IAD has been used, adapted and modified so many times that it often seems incomprehensible as a single framework. Below, I sketch out the most basic features of the framework.The IAD divides an investigation into three levels of analysis for studying "underlying factors" of an intsituion's success or failure – (1) exogenous variables, (2) action arenas, and (3) outcomes and evaluations.

1. 1. Exogenous variables include biophysical attributes of the shared resources, community attributes, and structural governance policies (formal or informal).Exogenous variables are also considered the "input" to a complex system.

In his overview of the framework Frischmann gives a simple example of this group, from the Maine Lobster fishing grounds, ". . . attributes might include the relevant biological characteristics of lobsters, such as the rates at which they age and reproduce; attributes of the community of fishermen, such as the proximity in which they live to others, the existence of familial relationships, and the skill sets needed for lobster fishing; and the rules—explicit or informal—that govern fishing." (Frischmann, 2013). The most crucial aspect of this level is that while individual attributes or variables are identifiable and observable, they need not be considered fully decomposable (Ostrom, 2009b) – meaning that the salient features of a commons are often thought to be "emergent properties" where the mutual constitution of people and objects (in the case of ICOADS technologies) create phenomena which are indivisible. The use of multiple research methods for the same institutional setting are often justified on the grounds of needing to understand these emergent properties (Ostrom, 2009b).

1. 2. An Action Arena – space where exogenous variables and actors interact, cooperate, and conflicts emerge. This level of the IAD places the stakeholders and the resources of the commons – as inventoried in level 1 – into a particular setting such as the harvest of a shared common field. Using the understanding gained from level one, the analyst observes this process and then identifies tangible outcomes, objective results and the way that conflicts from the past, or the present are

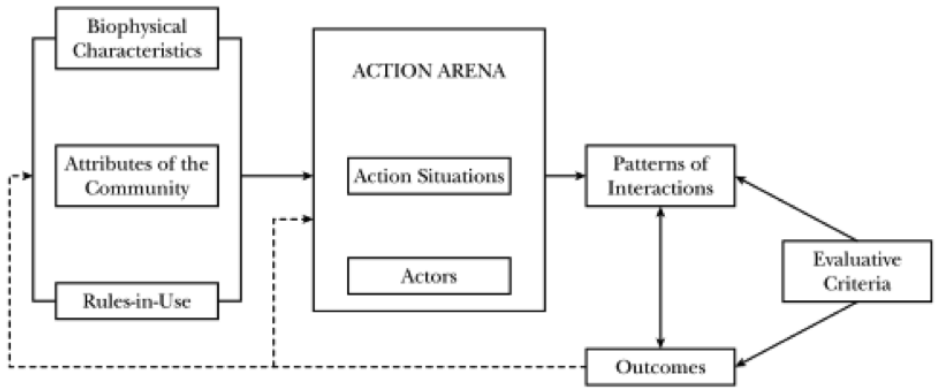


Figure 2: The framework of the IAD (Ostrom, 2005, p. 15)

voiced, contested, settled or deferred. This analysis can take place over long periods of time, to give a longitudinal account of action such as the restoration of an aquifer (Ostrom & Cox, 2010) or a statistical analysis of these processes through agent-based models or multi-modal network analysis (Axelrod, 1997).

1. 3. Outcomes and Evaluation – the results and feedback of action situations In the final stage of the framework an institution can be evaluated based on outcomes of the action arena; that is, how well an institution did or did not solve a collective action problem. Criteria for evaluation will vary by institutional setting, but usually includes calculation of transaction costs, such as (1) information costs (2) coordination costs; and, (3) strategic costs, or sustainability of the shared resource in terms of (1) efficiency in access and use (2) equity of distributed wealth or costs, (3) accountability for resource management, or (4) adaptability of the institution in light of these outcomes (Imperial & Yandle, 2005).

For commons made up of natural resources, of the type previously studied by institutional scholars: the boundaries were clear, the resource systems studied were small and easy to observe, solving problems was of high salience to appropriators, institutions were long-enduring and had evolved over time, and (5) extensive field observation was available (Ostrom, 2011) Each of these assumptions is complicated, if not completely opposite for peer produced commons of digital material. Notably, boundaries are unclear, resource systems (commons) are large, distributed and impossible to observe qualitatively, and institutions are rapidly evolving- often existing for short funding cycles that are of the 5-10 year range. While the IAD provides a starting point, the dynamic nature of purposefully built commons of digital objects requires much more innovation than a simple re-tooling of terminology (C. Hess & Ostrom, 2007). In the next section I review a proposal for the constructed cultural commons, which provides a novel way to overcome some of these limitations.

## Constructed Cultural Commons

In a broad ranging discussion of the purely functional account of common property regimes, three lawyers - Maddisson, Frischmann and Strandburg , propose a new framework for studying the cooperative work of cultural institutions facing collective action problems. In this account, "constructed cultural commons," are defined as, "environments for developing and distributing cultural and scientific knowledge through institutions that support pooling and sharing of that knowledge in a managed way" (Madison et al., 2010, p. 659). Constructed cultural commons are, as MFS explain, markedly different than the natural resource commons of Ostrom et al's study, "These environments are designed and managed with limitations tailored to the character of those resources and the communities involved rather than left to evolve via market transactions grounded solely in traditional proprietary rights" (Madison et al., 2010, p. 659)

Madison, Frischmann and Strandburg propose that in creating a unified framework for studying the success and failures of diverse cultural commons by aligning their "social role and significance" within nested institutions. In particular, their framework is to be used for works of pooled resources that are not subject to the same types of intellectual property laws that govern private property or common-pool resources. MFS's proposal does not suggest moving away from functionalism, but to add to it through a form of 'analytical narrative' (R. H. Bates et al., 2000), where "In proper proportion, a

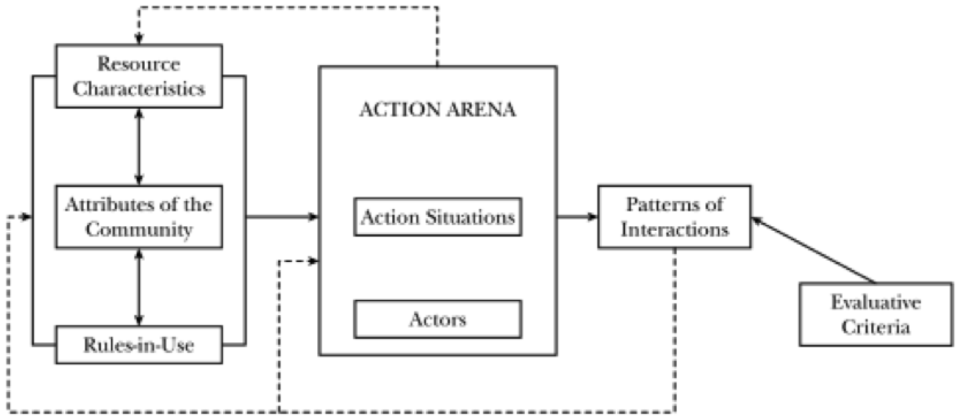


Figure 3: Madison, Frischman and Strandburg's modification the IAD for a Constructed Cultural Commons (Madison et al., 2010)

humanistic and metaphorical inquiry into information policy, on one hand, and a functional approach grounded in social science models, on the other hand" (Madison et al., 2010, p. 673). Or in other words, a unified framework that can account for new modes of knowledge production, distribution and the purposeful construction of cultural objects in physical and digital forms.

Their proposed framework achieves this through three major innovations with the IAD: 1. It emphasizes among distributed actors, and the constructed nature of the resources themselves (purposefully built objects as opposed to natural resources) 2. Where the IAD separates "outcomes" (level 2) and "patterns of interactions" (level 3) the constructed cultural commons framework treats these as iterative, mutually constitutive processes. 3. As a result of the more complex relationships between resources, participants, and governance structures– the "relevant" attributes of each may not neatly divide into categories.

In short, this is the acknowledgment of a "mutually constitutive" sociotechnical perspective.This innovation with IAD is therefore particularly useful for studying public goods, which do not fit cleanly into private or cooperatively owned property regimes. The quintessential case for constructed cultural commons are free and open source software projects such as Apache or Linux, but the authors note that the ambition of their framework is to include a diverse set of constructed commons such as the case studies they offer on patent pools amongst technology firms.

## Sociotechnical Interaction Networks (STIN)

The socio-technical interaction network is a framework published late in Rob Kling's life, producing only two publications that described its features through use cases having to do with scholarly communications (Kling et al., 2000, 2003). A broader definition in the second of these publications was that a STIN would be a, "conceptual framework for identifying, organizing, and comparatively analyzing patterns of social interaction, system development, and the configuration of components that constitute an information system" (Kling, McKim and King, 2003).

STIN was heavily influenced by actor-network theory in that the elements of a network are not treated as decomposable entities, but instead studied for the strength or weakness of their associations (i.e. Latour's dictum that "nothing can be reduced to anything else, nothing can be deduced from anything else, everything may be allied to everything else" (1988, p. 163)) is analogous to the "co-constitution" of the social and technical network that studies associations. The difference being that while Latour hopes to give an account of a specific moment in which a network of associations achieves (or fails) Kling is interested in the shaping of communication systems, and the purposeful design and engineering of associations within those systems. Another way to put the difference is that where Latour asks "What's going on here, really?" in the metaphysical sense, Kling asks, "What's supposed to go on, what do we want to go on, and how can we design a system to facilitate this?" in the normative sense. The former is concerned with creating an object-oriented ontology to be put to use by sociologists of associations (Harman, 2003; Latour, 2005), where the latter is, like the cyberneticists stating that "What can be studied is always a relationship or an infinite regress of relationships. Never a 'thing'" (Bateson, 2000).

Some assumptions that STIN and the socio-technical approach more generally accept are the following:

1. The social and technical are not meaningfully separable. This is the very idea of a mutual constitution between these two elements.

2. Theories of social behavior can and should influence technological design choices (STIN has a normative dimension)

3. Actors are embedded in multiple social relationships, only some of which are technologically mediated. Being a part of many networks, people may have conflicting commitments. An STS plays differing roles in the lives (professional, educational, etc) of an actor.

4. Sustainability and routine operations are critical and must play a role in determining design.

STIN has rarely been adopted, but is often cited for its potential to guide or inform work of a sociotechnical concern (Meyer, 2006). Studies where the framework has been used include Web Implementation Systems (Eschenfelder & Chase, 2002), Digital Libraries (Rosenbaum & Joung, 2004), and teams of Open Source Software development systems (Scacchi, 2005).

**Modeling a STIN**

In Kling, McKim and King's study of collaboratories they outline the following steps, noting that these are to be seen as "illustrative rather than enumerative" (2003).

- Identify a relevant population of system inter-actors

This is very similar to a traditional "stakeholder analysis" in systems development. STIN researchers attempt to understand the diversity of actors, their roles, and their needs with respect to the system being studied

- Identify core "inter-actor" groups

Uses results of first step to group actors - also, attempts to make clear the conflicts that may emerge between groups and between individuals that may be a part of many groups.

- Identify incentives

Kling et al. describe this as the "business model" of a STIN- asking "what would energize appropriate communication in the forum" of a scholarly communication system. Understanding the ways and means of sustaining that energy may be explained by a theory of social interaction explicitly, or implicitly.

- Identify excluded actors and undesired interactions

Understanding the sustainability of a STIN also depends on modeling what interactions, and what forms of interactions that actors do not want.

- Identify existing communication forums

This step is an attempt to characterize an actor (or group of actors) "communication ecology" . Kling et al. also instruct that this should be done with particular attention paid to how or why a new design might introduce competition in this ecology.

- Identify resource flows

In short, this is described as a "follow the money" exercise to track resources throughout a STIN.

- Identify system architectural choice points

After characterizing the STIN, this model proposes to identify system architectures and their "choice points", which refer to "a technological feature or social arrangement in which the designer can select alternatives"

- Map architectural choice points to socio-technical characteristics

This process combines all steps in proposing "combinations and configurations of features that are most compatible, viable, and sustainable." (Kling, McKim and King, 2003 p. 57)

## Multidimensional In-Depth Long-term Case Studies (MILC)

The last framework to be evaluated comes from the field of human computer interaction (HCI). Although this framework does not deal with sustainability per se, it is included for the following reasons:

- MILC's are used to study action situations over long periods of time. Thus, it provides insight as to how a framework might deal with longitudinal events, such as sustainable practices in a data archive.
- By focusing on design scenarios which are "situated" and highly responsive to contextual factors, the MILC framework offers a way to integrate sociotechnical scholarship which is incompatible with much of the IAD's functionalism.
- MILC's have a unit of analysis that is constructed, built, or purposefully engineered - as such, the framework is concerned not with simply cataloguing the existence of an object over time, but improving its features and performance along the way.
- Like STINs, a MILC has a normative dimension, but this framework includes a consideration of interventions that are design-oriented.

Schneiderman and Plaisant describe the "Multi-dimensional In-depth Long-term Case studies" by way of deconstructing its various terms (Shneiderman & Plaisant, 2006):

- **Multi-dimensional** refers to using observations, interviews, surveys, as well as automated logging to assess user performance interface efficacy, and utility.
- **In-depth** refers to the intense engagement of the researchers with the expert users to the point of becoming a partner or assistant.
- **Long-term** refers to longitudinal studies that begin with training in use of a specific tool through proficient usage that leads to strategy changes for the expert users.
- **Case studies** refers to the detailed reporting about a small number of individuals working on their own problems, in their normal environment (2006, p.1).

The outcomes of a MILC usually take two forms:

1. The refinement of the tool and an understanding of general principles or guidelines for the design of such tools.

2. The achievement of the expert users' goals, by way of their gaining some form of mastery over the tool.

Use of the MILC framework is limited by the need to have willing participants, and a stable field of study for long periods of time. As reported by Valiati, Freitas, and Pimenta in their use of MILC during a project that took twice as long as they had scheduled for completing a single case study, "performing multiple longitudinal case studies in a parallel way is a very hard task, due the difficulty of finding users to participate and the availability of the users during the study" (2008).

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